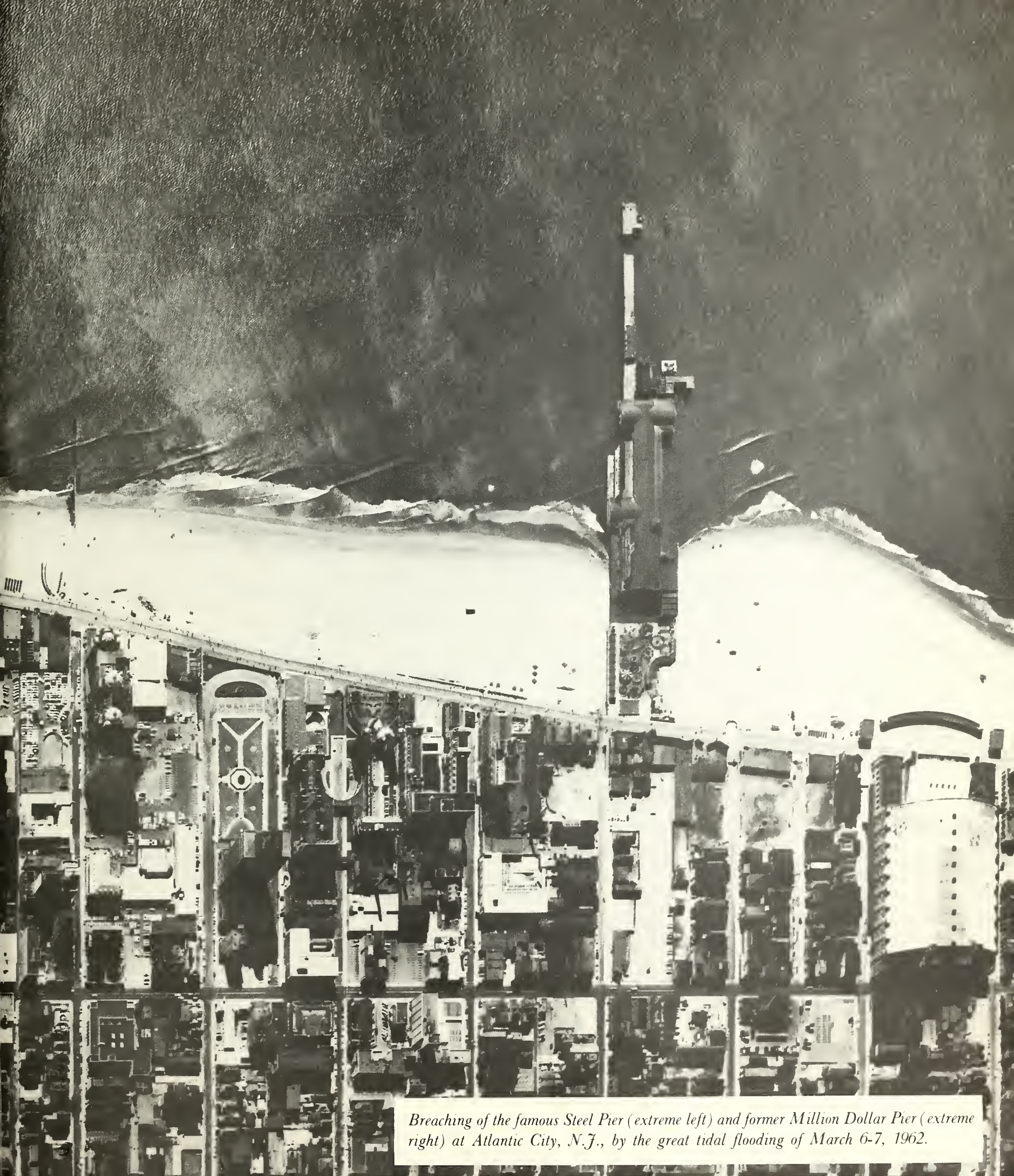
THE STRATEGIC ROLE OF PERIGEAN SPRING TIDES

In Nautical History and North American Coastal Flooding, 1635–1976

U.S.DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION



Breaching of the famous Steel Pier (extreme left) and former Million Dollar Pier (extreme right) at Atlantic City, N.J., by the great tidal flooding of March 6-7, 1962.

Courtesy of United Press International

Aerial photograph showing the extreme damage to homes along the beach at Point-o-Woods, Fire Island, N.Y., created by tidal flooding associated with the coincidence of perigean (proxigean) spring tides and strong onshore winds. This active coastal flooding persisted throughout five successive high tides, March 5–7, 1962.

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Fergus J. Wood
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Office of the Director

U.S. DEPARTMENT OF COMMERCE
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Foreword

Within recent years, increasing demands on the shoreline have led to its national redefinition as the "coastal zone." Thus emerged the concept of treating the area as a natural "system" in which multiple uses must somehow be accommodated. The sociopolitico, economic, and scientific debates that ensued have resulted in what is now known as "coastal zone management." This treatise deals with the natural forces at work in the domain of the coastal zone manager, and perhaps will lead him to ponder on events of Nature that should be considered in his planning. The manager must be aware that the shoreline portion of the coastal zone is a shifting triple boundary, fleeting by nature, and forever seeking a stability with sea, beach, and air that is never achieved. Here, where earth, sea, and sky meet, often to wash hands in mischief, is where the most violent physical action occurs in the coastal zone.

The National Ocean Survey, and its predecessor agencies, have lived and worked in the coastal zone for 169 years. Even after so long and active a tenure it still seemed reasonable that we should ask ourselves the question: "Have we overlooked anything that would be useful to the coastal zone manager, the planner, the developer, and the citizens who live in this increasingly popular locale?" For years we have published maps, charts, and tide tables. We have established tidal bench marks and geodetic control around the coasts and across the country, all necessary for the apportionment of appropriate jurisdictions among Federal, State, and local governments, between these governments and private landholders, and between our Nation and the rest of the world.

Accordingly, we began to think of other areas that might fruitfully occupy our attention. We examined many natural occurrences including coastal subsidence, shoreline erosion, loss of coastal marshlands, coastal development, shifting bottom topography, coastal currents, and tide observing systems, always keeping in mind the idea that something might have been overlooked that could be useful to those concerned with the coastal zone. Coastal flooding came under our scrutiny, which led Fergus Wood to examine what is known about the tides. He kept digging and studying all aspects of the tides, ranging from our batting average on tidal prediction to the historical effects of tides on man. It was out of such analytic studies that this work was born.

The tides affect man most adversely when coastal flooding occurs. Not all high tides cause flooding, nor do all coastal onshore storms. Given, however, a set of circumstances wherein uncommon tides, called perigean spring tides, coincide with strong onshore winds from an offshore storm, such as a nor'easter along the Atlantic coast, the coast will be flooded at all lowland points. The catastrophic event of March 1962 along the mid-Atlantic seaboard was such a circumstance and provided a grim reminder that two strong forces of Nature acting in concert can create havoc.

During the times of perigean spring tides, the controlling astronomical forces are enhanced. Sun, Moon, and Earth are aligned, the Moon is closer to the Earth, and along with the Sun, is exerting the increased and concentrated gravitational forces due to their alignment. The Moon is moving faster in its orbit, the length of the tidal day is increased, and there is created what Wood refers to as "a window for potential flooding." At these times the tides build up faster, tidal currents increase, and when accompanied by a strong onshore wind, the ocean waters pour into the estuaries faster than they can escape on the ebb. The pileup of water behind offshore bars results in a destructive breaching from the landward side, and the ocean begins to reshape the shoreline, moving whatever is in its path.

Fergus Wood is an interdisciplinary scientist. He treats the astronomy, meteorology, and oceanography in this volume in a thorough manner for the attention of the scientist. For the interested nonscientist, he has included a less technical discussion, and for the historian he has exhaustively investigated events of the past that were influenced by perigean spring tides. As a research geophysicist, he has approached cautiously another aspect of the perigean spring situation—how it affects the solid earth. The same forces responsible for perigean spring tides in the ocean also create enhanced earth tides, the results of which are obscure. In the present state of knowledge, there seems to be no satisfactorily provable connection, for example, between perigean spring tides, earth tides, and seismic events. But curious and openminded geophysicists are beginning to examine the connections, if any, between earth tides and earth movements, especially microseismic swarms. Perhaps this book will encourage them to look carefully at what, if anything, occurred in the solid earth on past occasions of perigean spring tides, notably of the "proxigean" type, which are explained in part II, chapters 3, 4, 5, and 8.

It has been my pleasure to encourage Fergus Wood in this work and to participate with him in many discussions on the research that went into it. I hope that the reader will find profitable the result which consumed nearly four years of his unflagging attention.

Gordon G. Lill

AUGUST 2, 1976.

GORDON LILL,
Deputy Director,
National Ocean Survey.

Author's Preface

PERIGEAN SPRING TIDES: A Potential Threat Toward Coastal Flooding Disaster

This book deals with the origin, nature, and impact of severe tidal flooding of lowland coastal regions resulting from the coincidence of astronomical and meteorological forces.

On March 6, 1962, such a catastrophic occurrence struck from the sea in the darkness of predawn, and for the following 65 hours inundated the entire mid-Atlantic coastline of the United States from the Carolinas to Cape Cod. This disastrous event resulted in a loss of 40 lives and over $0.5 billion in property damage. As other representative examples, severe tidal floodings of similar origin occurred in regions of the Atlantic coast on December 30, 1959, March 4–5, 1931, and April 10–12, 1918—and at points along the Pacific coast on March 6, 1970, February 3–4, 1958, and January 3–5, 1939. Still further floodings were experienced simultaneously *on both coastlines* on December 11, 1973, March 26, 1971, and January 6, 1931.

All of these instances of coastal flooding were caused by a special combination and reinforcement of the gravitational forces of the Sun and Moon producing unusually high tides—which were concurrently lifted onto the land by strong, persistent, onshore winds.

Such exceptionally high tides and their accelerated ocean currents—coupled with intense sea-surface winds—accompanied the total destruction of an offshore Air Force radar tower on February 12, 1963. The foundational erosion and subsequent toppling of the Marconi experimental transatlantic radio tower on Hatteras Island on April 4, 1915, was associated with a comparable situation of perigean spring tides and strong onshore winds. The previously mentioned astronomical alignment of Earth, Moon, and Sun—known as *perigee-syzygy*—also was present (although exerting a more limited influence due to the small tidal ranges encountered in the Gulf of Mexico) during the great Galveston, Tex., hurricane and tidal flooding of September 8, 1900. A computerized search of the scientific literature reveals that none of the above aspects of perigean spring tides has been analyzed and discussed in a thoroughly comprehensive manner.

In a more modern concept emphasizing the ongoing risk, this semiregularly recurring type of tide—when supported by sustained onshore winds—obviously can pose a threat to the development of offshore oil storage platforms and pumping stations engaged in the transfer or distribution of crude oil to coastal refineries.

A potential for inland as well as shoreline flooding is created by the increased amplitudes and strongly running currents associated with these tides, which may bring saltwater far up estuaries beyond the ordinary tidewater reaches. The alternating extreme low waters, if diluted by heavy rain, may exercise a severe detrimental influence on the oyster and hardshell fishing industries. Such tides likewise may impact adversely upon coastal wildlife sanctuaries, and interfere with the normal breeding cycles of freshwater fish.

At a low-tide phase occurring near a perigee-syzygy alignment, the extremely low waters both preceding and following the astronomically produced extremely high waters can cause the stranding of deep-draft vessels such as modern supertankers plying coastal waterways. This situation imposes an additional threat of oilspills and irremedial damage to the coastline. These and other influences of perigean spring tides which possess a definite practical impact on maritime commerce, the coastal ecology, and the status of the marine environment are thoroughly treated in this work. A definitive review of these numerous special properties of perigean spring tides and their effects constitutes the *raison d'être* for the present monograph. Because of the many different degrees and grades of perigean spring tides, the documentation and analysis of a large number of examples has been necessary.

In pursuit of this supporting material, a detailed investigation was instituted, based upon interdisciplinary sources of data. With the cooperation of the U.S. Naval Observatory, a computer printout was prepared, indicative of the considerable variation in astronomical alignments responsible for perigean spring tides throughout the 400-year period from 1600 to 1999. With the dates of such augmented tide-raising forces duly tabulated, a systematic search was begun through heretofore uncoordinated accounts of tidal flooding on the North American coastline as presented in newspaper and other more definitive sources extending historically to the year 1635. The pieces of a complex puzzle began to fall in place.

The documentation of more than a hundred of these major coastal flooding events of the past, and a discussion of the associated hazards to maritime commerce, seashore habitations, and the coastal environment posed for the future by such recurring flooding events have been set down respectively in tabular and case-study form in this work.

Part I summarizes the historical, practical, and environmental aspects of perigean spring tides. In the second, scientific part of the work, the precise astronomical factors causing close perigee-syzygy alignments under certain conditions are explained in detail. The associated increased perturbations of the lunar orbit which result in diminished Earth-Moon distances, enhanced gravitational forces upon the Earth's ocean waters, and augmented tidal amplitudes are mathematically analyzed and described.

A numerical quantifier (known as the delta-omega syzygy coefficient) designed to serve as a predictor term in establishing the relative potential for tidal flooding generated by such astronomically augmented tides (when supported by the necessary meteorological conditions) also has been developed.

On December 26, 1973, based on the foregoing research, the first actual warning of potential tidal flooding during a period bracketing a very close perigee-syzygy alignment of January 8, 1974, was announced to the public by NOAA through the press, radio, and television media. A counteracting high atmospheric pressure system and calm winds prevented any further rise of the very high astronomical tides produced along the east coast on this date. However, front-page headlines in the *Los Angeles Times* for January 9 told of the "tidal assault" supported by the strong onshore winds of the day before. The accompanying news article summarized the extent of coastal damage and the advance opportunity provided for preventing damage to homes and shoreline installations by sandbagging, backfilling, and other precautionary measures.

A confirming instance of tidal flooding based on the same very close perigee-syzygy alignment (termed *proxigee-syzygy* throughout this work), in which the resulting *proxigean spring tides* were accompanied by onshore winds, occurred along the western and southern shores of Great Britain on January 11–12, 1974. The 3-day time delay is a function of oceanographic factors. A second tidal flooding (related to a similarly announced perigee-syzygy alignment a month later) occurred along the southern coast of England on February 9. Yet another example of active astronomical tidal flooding potential, contributed to by strong onshore winds, materialized on March 17, 1976, when 5 feet of seawater flooded at Halifax, Nova Scotia, following considerable tidal erosion in lowland coastal regions of Massachusetts, New Hampshire, and Maine.

Again, on January 8–9 and January 11–12, 1978, perigean spring tides associated with the perigee-syzygy alignment of January 8 were reinforced by strong onshore winds. The resulting high waters caused serious flooding damage both along the lowland shores of southern California and New England, and those of Great Britain, respectively. On February 6–7, 1978, significantly one lunar month later, these incidents were followed by even more severe tidal flooding in nearly identical locations on the east and west coasts of the United States.

The documented analysis of such major tidal flooding episodes of the past, and the rational precautionary measures to be taken to prevent extensive damage from such flooding events in the future, constitutes a considerable portion of both parts I and II of this monograph. An analysis of the astronomical principles underlying the production of these tides, the varying forces which create them, and the perturbations in the lunar orbit which modify the amplitude of these forces and the duration of time in which they are active, all are contained in the second, scientific portion of the work. The last chapter contains a tabulation of all dates vulnerable to especially severe tidal flooding (should the weather and wind conditions also conspire) down to the year 1999.

A Definitive Scientific Study of Perigean Spring Tides

Among the results of the research documented in this publication are:

1. Correlations between more than 100 cases of major tidal flooding—sustained over 293 years of history—and the coincident existence of perigean spring tides. This volume also includes separate case studies of outstanding examples of tidal flooding along the North American coastline, supplemented by tidal growth curves, daily weather maps, contemporary news accounts of the flooding damage, and other data.

2. Discussion of certain representative cases of perigean spring tides which have altered the course of naval history.

3. Evaluation of the practical impact of perigean spring tides on such diversified areas as coastal and inshore navigation, marine engineering, hydrological runoff, bioecological imbalance, and erosional damage to the coastal environment.

4. Examination of various instances of ship groundings, strandings, and collisions caused by the extreme low-water phase associated with perigean spring tides—or by their accompanying strong currents.

5. Delineation of examples of unusual tidal flooding which reached far inland, as the result of the coincidence of hurricanes and perigean spring tides. A comparison is made between the flooding potential of hurricanes with and without the association of perigean spring tides, also between the flooding damage caused by hurricanes and by onshore winds generated by winter storms occurring coincidentally with perigean spring tides.

6. Expansion of those portions of classic tidal theory involving the mean positions and mean motions of the Moon and Sun to suggest further refinements in computed heights and amplitudes based upon the *true* positions and motions of these bodies and the *true* motion of perigee.

7. Analysis of the perturbational influences of the Sun on the orbit of the Moon during the critical period resulting from the alignment of perigee and syzygy. The results incorporate entirely new concepts substantiated by U.S. Naval Observatory data which provide a considerable modification of previous theories regarding the direction and speed of motion of the lunar perigee at these times.

8. Formulation of appropriate new terminology for the classification of a range of intensities of astronomically produced perigean spring tides. Included among these developments is the origination of the needed additional descriptor terms *proxigee* and *exogee*, and a system for categorizing various degrees of perigean spring tides based upon the lunar parallax.

9. Derivation of a numerical coefficient or index expressing tidal flooding potential—which combines astronomical, hydrographic, dynamical oceanographic, meteorological, and other factors. Through auxiliary tables published in the book, the astronomical portions of this multiparameter index at the time of any perigee-syzygy alignment are immediately available to marine weather forecasters, beachguards, harbormasters, Coast Guard officials, civil defense agencies, and others directly concerned with coastal hazards and with protection against tidal flooding.

10. Review of numerous interdisciplinary fields in which the astronomical phenomenon of perigee-syzygy—and the increased gravitational forces it entails—might show some causal connection with other geophysical phenomena. The areas cited include the known augmentation of earth tides and ocean loading, the possible triggering of earthquakes, influences on geodetic leveling and deflection of the vertical, and geomagnetic effects. The possible excitation of biological tidal rhythms is also considered.

A Note of Caution Relative to the Interpretation of Data

A brief commentary of purely objective nature is desirable in order to satisfy the author's sense of responsibility to the scientific community concerning the content of this work. The following treatise involves, in part, a comprehensive series of case studies on perigean spring tides covering 341 years of historical record. The analytical deductions made have been rigorously tested against this complex of empirical data. Out of this research effort, certain patterns of consistency have emerged which are beyond the realm of random chance and which render scientifically tenable the development of appropriate principles relating to the strong flooding potential of perigean spring tides. Coincidentally, certain definite conclusions are possible concerning the strategic importance of these tides in producing tidal flooding—if reinforced by strong onshore winds. In addition, evidence from this research supports a considerable credibility in the practical significance of these tides resulting from their economic, environmental, and ecological influences.

A peremptory note of caution must be sounded, however. It is essential to observe that, because of the complexities involved in tidal prediction, many technical statements in connection with the tides must be accompanied by qualifications, reservations, and limitations—and, upon occasion, by individual exclusions and exceptions. One of the easiest available pitfalls and most incautious professional errors it is possible to commit in presenting any aspect of the tides is to allow any overgeneralized statement in connection therewith.

The empirical data and analytical procedures used in this volume for determining tidal flooding potential are those applicable specifically to lowland regions on the Atlantic and Pacific coasts of North America. Likewise, although any measure of tidal flooding potential derived therefrom may pertain unequivocably to a dozen or so related tide stations responsive to the same resonance mode, it may be totally or partially inapplicable to a location possessing different harmonic constants situated, perhaps, only a few score miles from the more consistent stations. In short, making any too general statement regarding tidal responses subject to a purely astronomical influence (in this case, a combined lunisolar influence) is, at best, a dangerous undertaking. Such astronomical forces will inevitably be modified by local oceanographic conditions, by tidal harmonics, and by such other variables as geographic latitude and longitude, sea-floor and coastal hydrography, strong hydrological runoff from the land, climate, season, and weather.

In this concept, it would be totally pretentious to make unqualified statements for the absolute, permanent validity of either the Π *factor* or the $\Delta\omega$-*syzygy coefficient* forming a part of it (cf., ch. 8) which are both subject to the need for continuing test and evaluation over time (permitting any desirable modification in their constituent parameters). A working hypothesis advanced upon the strength of evidence provided by even a large and diverse number of cases, however widely distributed in terms of time, hemispheric geography, and local conditions, is acceptable only insofar as it can adequately represent all circumstances throughout the entire period of past history for which observed data are available, and be capable of similar accurate reproducibility of tidal flooding potential in the future—on a worldwide basis. This word of caution is not intended in any sense to weaken the analytic procedures or formulae developed in this investigation, but only to point up that ultimate definitiveness of the method requires consideration to a massive, totally representative, and globally adequate body of tide data.

The groundwork, however, is at hand. The rate-of-growth tide curves alone in this project involved the computation and plotting of over 18,000 individual data points. More than 100 years of daily tide tables were available, extending back to the original "High Water Only" predictions of the U.S. Coast Survey (which later became the U.S. Coast and Geodetic Survey and is now the National Ocean Survey, a component of the National Oceanic and Atmospheric Administration). Separate tide tables were first published by the Coast Survey in 1866, following upon a series of simple tabular data showing the relationship of the tides to the "full and change of the moon" which were issued in the annual volumes of the *Report of the Superintendent of the Coast Survey,* starting in 1859. All such basic data have come under scrutiny, as appropriate to this study, for the validation of perigean spring tides.

On the meteorological side of the research effort, 105 years of daily surface synoptic weather maps (published since 1871, successively, by the U.S. Signal Corps, the U.S. Weather Bureau, and the present National Weather Service) were reviewed for the presence or absence of strong, persistent, onshore winds at the established times of perigean spring tide. Evidences of accompanying tidal flooding were then sought from newspaper, journal and special report literature dating back to the early colonial period in American history.

From the astronomical point of view, the task of correlating these tidal and meteorological data was made possible through the cooperation of the U.S. Naval Observatory in providing a computer printout of all perigee-syzygy alignments having a separation-interval less than, or equal to $\pm 24^h$, occurring during the 400-year period from 1600 to 1999.

The exact method of application of these numerous sets of data, and the principles of random selection utilized to provide a space-saving but statistically valid base of comparison throughout widespread geographic locales on both the east and west coasts of North America, in succeeding decades of history, in different seasons of the year, and distributed at various times of the day, is thoroughly explained on pages 10–14 and 327–331 of this work. The alphanumeric system for coding individual tidal flooding events, making possible a ready intercomparison between the associated astronomical, meteorological, and oceanographic circumstances—as well as a comparison with documented accounts of the accompanying tidal flooding—is described in these same pages.

It should be emphasized from the outset that the evaluations made in this treatise concerning the effects of perigean spring tides do not overlook the possibility that other lesser influences (such as sufficiently strong onshore winds coinciding with *ordinary spring tides*) may cause tidal flooding of generally smaller degree—nor do they in any way play down the role of hurricanes as a very major source of coastal flooding. However, this study does focus upon the particularly vulnerable role of perigean spring tides, with supporting wind accompaniment, in producing such coastal flooding effects.

The inherent danger of misconstrual of scientific information on the part of sources bent on sensationalizing such potentially catastrophic events of Nature through a lack of awareness of the total forces and concepts involved has been fully noted on pages 406–408. Further education and enlightenment of the large segment of the coastal population subject to the effects of such devastating flooding is the most effective method to forestall the unnecessary and costly confusion resulting from this type of misrepresentation. The purely scientific conclusions derived from this study are summarized both in the immediately preceding section of the preface and in the abstract which precedes the main text.

* * * * * * *

Finally, a note of apology is extended to professional colleagues for the author's shortcoming in not more rigorously avoiding certain minor redundancies in the following pages of text—an inconsistency which belies previous experiences in encapsulating some 180 articles written on astronomical and geophysical subjects in seven different encyclopedias and reference sources. Such are the vicissitudes of Government agency reorganization that, early in this project, the author found himself pursuing alone, not only the necessary research aspects, the writing, associated computations, compilation of tables, and drafting of diagrams, but also the editing of his own manuscript—while at the same time racing a deadline for publication before his intended retirement from Government. Under these demanding circumstances, the inevitable result was a certain duplication between the contents of small sections of different chapters, prepared variously, as the associated analyses were accomplished, over a period of more than 4 years.

On the positive side, somewhat salving a conscientious attitude regarding such compositional refinement, these same technical areas of the work may, however, benefit from an additional self-containment helping to minimize cross-referrals between chapters by readers who are less conversant with the subject material. A similar occasional repetition of nomenclatural definitions—useful to a prospective student of the subject in recovering his bearings among the otherwise complex technical development—requires, perhaps, a lesser apology. The author naturally assumes responsibility for any errors of technical nature which may, through the very comprehensiveness of the work, have escaped attention in reviewing proofs on an accelerated time scale.

Acknowledgments

The number and variety of persons contributing to, and in a very real sense ultimately responsible for, the realization of this complex technical monograph over nearly a 5-year period represent a degree of individual effort making regrettable an inability more properly to credit the assistance of each, in fitting detail. Such extensive individual cooperation may, parenthetically, be regarded as indicative of the wide range of personal interests in a subject so meaningful to those utilizing the coastal environment.

From the very outset of the investigation as a scientific concept suggested for further study—through its subsequent development into a full-scale project as pieces of the puzzle began to fall into place—and the intensive research

endeavor culminating in the present volume—the continuing interest, support, and personal encouragement of Dr. Gordon G. Lill, deputy director of the National Ocean Survey, and the matching confidence of its director, Rear Admiral Allen L. Powell, have provided a staunch undergirding for the work.

Over this same period of monograph preparation, the close cooperation, interdisciplinary rapport, and many stimulating hours of discussion with Dr. Thomas C. Van Flandern, lunar specialist in the Nautical Almanac Office, U.S. Naval Observatory, have contributed immeasurably to the technical significance and completeness of the project. Through his assistance, and that of Dr. P. Kenneth Seidelmann, director of the Nautical Almanac Office, and Dr. P. M. Janiczek, the extensive data presented in table 16 became possible—for which the availability of the computational facilities of this observatory is also duly acknowledged.

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Special appreciation must be extended to Mr. Francis X. Oxley, formerly chief of NOAA's Photographic Section, for his meticulous reduction and compilation processing of weather maps and composite overlays providing many of the illustrations for this work. He was assisted by Mr. Harold M. Goodman and Mr. John A. Roseborough. These photographic reproductions were initially made possible through the exacting negative copy work accomplished by Mr. Joseph E. Bradshaw, and Mr. Robert C. Robey, Jr., under the direction of Mr. William C. Bugbee, formerly chief of the photographic laboratory in the National Ocean Survey's (Chart) Reproduction Division.

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provided by the William L. Clements Library of the University of Michigan and the Ships' Histories Branch, Naval History Division, U.S. Navy Department. Mr. Timothy C. O'Callaghan aided with the compilation of the bibliography and index. Contributions of illustrative material were made by the many organizations to which individual credits are given as a part of the figure captions throughout the treatise. The Library of Congress provided the source for reproduction of many early newspaper accounts of tidal flooding.

Typing and revision of the extensive manuscript through its numerous stages of preparation was accomplished by Mrs. Mary Lou Lapelosa, to whom appreciation is also due for handling the many secretarial duties attendant upon the project, and for maintaining the considerable quantity of graphic material connected with the publication. A special tribute is owing to Miss Rhonda M. LaSaine, summer employee, for a diligent research application to Library of Congress newspaper sources, and to Ms. Beatrice S. Drennan, NOS, for similar assistance with resource literature. During the early stages of monograph production, support in preparing certain of the diagrams used was provided by Mrs. Gayle Brodnax.

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To all of the above, the author expresses his permanent gratitude.

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The Basic Theory of the Tides

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Abstract

Tides are caused by the gravitational attractions of the Moon and Sun acting upon the oceans and major water bodies of the Earth. Two times during each month, at new moon (conjunction) and full moon (opposition), the Earth, Moon, and Sun come into direct alignment in celestial longitude and, in the combination of their gravitational forces, enhanced tide-raising forces result. Tides produced at these times are called *spring tides*. Since the lunar orbit is elliptical in shape, once each revolution the Moon also attains its closest monthly approach to the Earth, a position known as *perigee*.

Ordinarily, the passage of the Moon through perigee and the alignment of Moon, Earth, and Sun at new moon or full moon (either position being called *syzygy*) do not take place at the same time. Commensurable relationships between the lengths of the synodic and anomalistic months do, however, make this possible. On the relatively infrequent occasions when these two phenomena occur within 1½ days of each other, the resultant astronomical configuration is described as *perigee-syzygy*, and the tides of increased daily range thus generated are termed *perigean spring tides* or, simply, *perigee springs*.

Whenever such alignments between perigee and syzygy occur within a few hours or less of each other, augmented dynamic influences act to increase sensibly the eccentricity of the lunar orbit, the lunar parallax, and hence also the orbital velocity of the Moon itself. Such solar-induced perturbations also reduce the Moon's perigee distance in each case by an amount which is greater the closer is the coincidence of alignment between these two astronomical positions, but which also fluctuates with other factors throughout the years. The tide-raising force varies inversely as the cube of the distance between the Earth and Moon (or Sun). On certain occasions, lunar passage through perigee involves a particularly close approach of the Moon to the Earth. To distinguish these cases of unusually close perigee, the new term "proxigee" has been devised, and the associated tides of proportionately increased amplitude and range are designated as "proxigean spring tides."

Evidences presented in this technical monograph indicate that the appreciably enhanced influences on the tides produced at the time of proxigee-syzygy are revealed, not so much in increasing the height of the tide (usually a maximum increase of about 0.5–1 foot above mean high water springs) but in accelerating the *rate* at which these augmented high waters are reached. This accelerated growth rate in the height of the tides, together with an increased horizontal current movement, creates a sea-air interface situation particularly susceptible to the coupling action of surface winds. Although the perigean spring tides do not, of themselves, constitute a major flooding threat to coastlines, friction between strong, persistent, onshore winds and the sea surface can raise the astronomically produced tide level to cause extensive flooding of the coast in lowland regions.

In addition, at the times of perigee- (proxigee-) syzygy, various dynamic influences combine to lengthen the tidal day, increasing the period within which the enhanced tide-raising forces, effective for some few days on either side of the perigee-syzygy alignment, can exert their maximized effects.

In this monograph, covering a 341-year period of history relative to the coastal environment of North America, a large number of examples of major tidal flooding produced by the combination of the above causes have been collated to provide a detailed case study. A composite table of 100 such cases, including all pertinent astronomical and meteorological source data, has been compiled. Graphic, textual, and mathematical analysis have been used to demonstrate the individual astronomical, oceanographic, meteorological, hydrographic, climatological, and hydrological influences which are involved during the production of the phenomenon commonly referred to as a "storm surge." Quantitative correlations between these various factors have been established.

A proposed new index of tidal flooding potential based upon the combination of astronomical influences augmenting the tides at the times of perigee-syzygy and known as the *Δω-syzygy coefficient* has been developed. This has been combined with other physical quantities representative of the local and prevailing tidal, meteorological, and hydrographic circumstances to establish a second index known as the *Π factor*. The latter term is designed to provide a quantitative measure of the probability of tidal flooding occurrences along a lowland coastline, should strong, persistent, onshore winds coincide with perigean spring tides. In contrast to the traditional method which involves a simple consideration to the highest tides of the year to determine flooding potential when such tides are accompanied by strong onshore winds (a procedure which can be shown to be both ambiguous and erratic in numerous instances), the combination of the Δω-syzygy coefficient with appropriate meteorological indicators is demonstrated to be an effective new tool for the evaluation of tidal flooding potential at coastal stations having a daily tidal range of 5 feet or more. The usefulness of this method can be further enhanced by future empirical refinements.

The particular vulnerability to tidal flooding exhibited by those perigean spring tides which possess a sharply accelerated rate of growth is one of the primary points of consideration in this monograph, inasmuch as the graphical-analytical methods applied do not appear elsewhere in scientific literature. Separate methods for obtaining a meaningful rate of tide growth in the case of both semidiurnal and mixed tides are shown. Such rate-of-growth tide curves are presented for actual cases of tidal flooding occurring over a wide range of latitudes, on both the east and west coasts of North America. These specially analyzed instances of coastal flooding are randomly chosen throughout all months of the winter storm season for a wide range of stations and are distributed, in each decade, over 80 years of record to permit a scientifically representative basis of correlation between the circumstances of tidal flooding and associated astronomical and meteorological data. Numerous examples of perigean spring tides accompanied by nearly simultaneous tidal flooding on both the Atlantic and Pacific coasts—and other floodings displaying a definite relationship to various astronomical cycles of perigee-syzygy—are included. The observed and predicted hourly height tide records for selected cases of tidal flooding are compared to show the separate effects of astronomical and wind actions.

A selection of daily synoptic weather maps matching the incidents of tidal flooding is used to demonstrate the contributing influence of strong onshore winds; an equal number of cases of nonflooding on occasions of perigean spring tides which were not enhanced by strong onshore winds is included to emphasize this necessary meteorological accompaniment. Supported by such winds, the far greater coastal flooding potential of perigean spring tides compared with ordinary spring tides or other tidal situations—often exceeding the inundating effects of hurricanes—is clearly pointed out. The always devastating effects of the combination of a hurricane with perigean spring tides is also discussed. Selected cloud-cover photographs made from weather satellites near the time of flooding perigean spring tides are incorporated in the treatise to reveal the exact atmospheric frontal conditions and disposition of each low pressure center responsible for strong onshore winds.

In the preliminary chapters, which trace the effects of perigean spring tides upon nautical history, navigation, marine engineering, and marine science, the various practical, economic, environmental, and ecological influences of these tides are outlined. This evaluation includes the combined effects of the elevated high waters, their corresponding low-water extremes, and the accompanying accelerated flood and ebb currents. In the final chapter, various other possible geophysical effects related to the phenomenon of perigee-syzygy and the increased gravitational forces producing perigean spring tides are discussed.

Part I—Background Aspects

Chapter 1. Representative Great Tidal Floodings of the North American Coastline

LITTLE did our colonial forefathers know that, within 5 years after they settled in Massachusetts Colony early in 1630, their New World home would be beset by disaster involving two natural forces of a type with which they had no previous experience, but whose enormously destructive influences upon life, limb, and property they and subsequent generations would have occasion to witness repeatedly throughout ensuing years. This first recorded coastal flooding of catastrophic proportions on the American continent happened in the fall of 1635. Like other early incidents of this type, it has never been thoroughly analyzed from the standpoint of its complex natural origins. Although purely meteorological factors are commonly given as the cause of such coastal flooding phenomena, certain specific astronomical tide-raising forces of periodic nature are also definitely involved, whose specific contribution will form the subject of the present study.

The Evidences From History

William Bradford, author of *History of Plimoth Plantation,* wrote dramatically of the impact of this early coastal flooding event which occurred on August 14–15, 1635, Old Style Calendar.[a] A portion of his narrative follows:

"This year the 14[24] or 15[25] of August (being Saturday) was such a mighty storm of wind and raine as none living in these parts, either English or Indians, ever saw. Being like (for the time it continued) to those Hurricanes and Tuffoons that writers make mention in the Indies. It began in the morning a little before day, and grue not be [sic] degrees, but came with a violence in the beginning, to the great amasmente of many.—It continued not (in the extremities) above 5 or 6 hours, but the violence began to abate. The signes and marks of it will remaine this 100 years in these parts wher it was sorest." [1]

An additional account of this great coastal storm and accompanying tidal flooding in colonial New England appears in a contemporary work by Nathaniel Morton titled *New England Memorial* in which the event likewise is described as a disaster-causing one that:

". . . blew down houses and uncovered divers others; divers vessels were lost at sea in it, and many more in extreme danger. It caused the sea to swell in some places to the southward of Plymoth, as that it arose to 20 feet right up and down, and made many of the Indians to climb into trees for their safety . . . It began in the southeast, and veered sundry ways, but the greatest force of it at Plymoth, was from the former quarter, it continued not in extremities above 5 or 6 hours before the violence of it began to abate; the mark of it will remain this many years, in those parts where it was sorest; the moon suffered a great eclipse 2 nights after it." [2] [At 9:49 p.m., 75° W.-meridian time, on August 27.]

CASE NO. 200—*Perigean Spring Tides* (near the time of a total lunar eclipse).

The last statement is that which has been generally overlooked in previous accounts, attributing the flooding entirely to winds. As noted in footnote (c), on page 7,

[a] For the purpose of exact comparison of astronomical, tidal, and meteorological events in the historical portion of this work, all dates given in the Old Style or Julian Calendar must be corrected by the addition of 10–11 days to give the corresponding date in the New Style or Gregorian Calendar, our present usage. The New Style date is indicated in square brackets following all such early dates quoted. Some of the cases of coastal flooding under discussion occurred prior to 1752. In this year, a change was made in England and throughout the British Colonies (including America) from the Julian Calendar (Old Style) to the Gregorian Calendar (New Style). This change came about from practical necessity.

By the 16th century, because of an astronomical phenomenon known as "precession of the equinoxes," the difference between the Julian Calendar year, invented by the Alexandrian astronomer Sosigenes, and the period of the Sun's apparent annual movement with respect to the vernal equinox amounted to 10 days. Continuing divergence threatened to throw out the existing alignment between the calendar months and the seasons. It therefore became necessary to drop 10 days from the Julian Calendar, and by a new system of accounting for Leap Years, to convert from the Julian Calendar to the Gregorian Calendar. (cont. on next page)

[1] Superior figures refer to sources listed at end of book.

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the same alignments of Sun, Earth, and Moon responsible for either solar or lunar eclipses [b] provide a geometric reinforcement of the gravitational forces of the Moon and Sun and thereby also augment the tide-raising forces present. The tidal forces are also sometimes further amplified by a special proximity of the Moon to the Earth resulting from such alignments.

What the inhabitants of the Massachusetts Colony did not know was that this great coastal storm very nearly coincided in time with another phenomenon of nature—the astronomical condition known as *perigee-syzygy* (see page 5 under "Technical Commentary"). In this phenomenon, the average between the exact time of full moon and that of the Moon's closest monthly approach to the Earth occurred between August 28 and 29 (Gregorian Calendar), within 2 days of the maximum intensity of the storm. With a significance which will appear in later discussions (see chapter 7), the separation in time between perigee and syzygy on this occasion also was less than 42 hours. This comparatively small difference in time between perigee and syzygy is an indication of the combined, nearly coincident application of the tide-raising forces of the Sun with those of the Moon—the Moon being at its monthly position of closest approach to the Earth, and in addition being brought by solar dynamic influences to an even smaller separation from the Earth.

In consequence of these enhanced gravitational forces, tides possessing an exceptionally great rise and fall known as *perigean spring tides* were produced. Subject to the simultaneous action of strong, persistent, onshore winds (serving to reinforce water movement toward and onto the land), severe tidal coastal flooding was a near-certainty. With onshore winds prevailing from southern Massachusetts through Maine to Cape Sable, Nova Scotia, together with exceptionally high astronomical tides, their combined effects were felt over this entire region in severe coastal flooding and extensive damage. At Buzzards Bay, and Providence, R.I., the tides reached heights of 20 ft.

With consideration to all related factors, and in maintaining a proper perspective between the combined astronomical and meteorological forces responsible for coastal flooding, it is necessary that the meteorological conditions at this time be carefully documented.

Governor John Winthrop of the Massachusetts Colony also kept a journal in which, under the date August 16 [26], he cites the meteorological conditions prevailing at the time and notes that, at midnight of this date, a moderate southwest wind of the previous week changed suddenly to a violent northeast gale. He states that the force of the storm was sufficient to destroy houses in Boston, and to separate the cables of ships in the harbor. The strong gale blew steadily off the water for 8 hours, further heightening the evening high tide, and then shifted as abruptly to the northwest, now blowing offshore.

In his diary account, corresponding to the Gregorian Calendar date August 26, Winthrop relates:

"About eight of the clock the wind came about to N.W. very strong, and it be then about high water, by nine the tide was fallen about three feet. Then it began to flow again about one hour and rose about two or three feet, which was conceived to be that the sea was grown so high abroad with the N.W. wind, that, meeting with the ebb it forced it back again." [3]

The impeding and forced backing up of the outgoing (ebb) tide by the next succeeding incoming and wind-driven (flood) tide resulted in two high tides within far less than a 12-hour period—in itself an unusual phenom-

(cont. from preceding page)

Although this Gregorian or New Style Calendar was adopted throughout most of the Roman Catholic countries in 1582, Protestant countries held out, and only in 1752 (because of the steadily increasing time difference) England and her colonies dropped 11 days from the calendar previously used. In comparing dates prior to 1752 with dates on the modern Gregorian Calendar, the difference must be allowed for, and results from the somewhat different procedures used in determining those century years which are Leap Years under the two systems. In the Julian Calendar, all century years divisible by four are regarded as Leap Years. According to the Gregorian Calendar, only those century years divisible by 100 which are also divisible by 400 (or whose first two digits are divisible by four) are considered to be Leap Years. Thus, in the Julian Calendar, 1600, 1700, 1800, and 1900 are all Leap Years.

Subsequent to the change in 1752, the difference between the two systems had increased to 12 days by 1800 and 13 days by 1900. However, in chapter 1, only Julian Calendar dates occurring between March 1, 1500 and February 18, 1700 (requiring a 10-day correction) and between February 19, 1700 and September 3, 1752 (requiring an 11-day correction) overlap the computer printout of table 16. Since the latter dates are given in the New Style Calendar, either 10 or 11 days must be added to the Old Style dates to convert them to this Gregorian system. The fact that, prior to the year 1752, the calendar year in England and her colonies also began on March 25 rather than January 1, as thereafter, also accounts for the usage of a dual year in conjunction with dates prior to 1752, where the period January 1–March 25 is involved (e.g., February 24, 1722/23).

[b] In Theodor Ritter von Oppolzer's *Canon der Finsternisse* (1887) all eclipses of the Sun between 1207 B.C. and A.D. 2161 and lunar eclipses between 1206 B.C. and A.D. 2163 are cataloged together with pertinent astronomical data. This lunar eclipse of August 1635, the midpoint of whose total phase occurred at 0249 G.c.t. on August 28 (New Style Calendar), is listed as having a magnitude of 18.1 on an arbitrary 22.8-point scale representing maximum central totality. This value indicates a well-centered eclipse, with the Sun and Moon in closely opposite (gravitationally reinforcing) longitudes and declinations. The tidal forces would be augmented in proportion.

enon and, as will be discussed in later instances, one very conducive to tidal flooding (e.g., ch. 7 "Meteorological Aspects . . .," case 4.

The sequence of wind shifts noted by John Winthrop was from southwest (for a week) to a strong northeast gale—at midnight of August 16[26]—swinging around to a strong northwest wind—at 8 a.m. on August 17[27]. He adds that the morning high tide was *depressed* 3 feet in 1 hour by this strong *offshore* wind. The storm is described as being felt as far north as Cape Sable, Nova Scotia, but possessing maximum strength south of Boston. William Bradford suggests its similarity to hurricanes and "tuffoons" of the Indies. This violent storm is, indeed, included among a list of hurricanes occurring historically on the east coast of the United States.[4]

So-called "storm-surges" and coastal flooding associated with hurricanes have been widely treated in the scientific literature from a meteorological standpoint (see Bibliography) and will not, therefore, be extensively discussed in this work. Hurricanes possess sufficiently strong wind velocities to cause coastal flooding, in varying degrees, at any phase of the tides—although, as will be seen in subsequent comparisons between various types of hurricanes involved in coastal flooding, *wind* damage is of greater consequence where astronomically induced high tides are not an immediate accompaniment. The present and a few subsequent examples are included to show the extent to which the tidal *flooding* influence of a hurricane may be further augmented by coincidence with a perigean spring tide to produce coastal inundation (in addition to wind damage) of extremely disastrous and destructive proportions. The extensive tidal flooding damage experienced in Massachusetts, Rhode Island, and Connecticut in 1635 is a typical example. This strong tidal flooding is the first which was made a matter of record in American history, but was by no means the last, as attested to by subsequent, similarly documented examples.

The additional flooding potential resulting from the combination of a hurricane with perigean spring tides—and the extremely hazardous effects of the combination of perigean spring tides with severe coastal storms in winter—are evaluated, in their relative significance, in chapter 7. It is an observed fact that a fast-moving hurricane does not usually provide as much time for a buildup of water level by friction at the air-sea interface as does a stagnant, offshore extratropical storm possessing a long overwater wind path.

By contrast, the special setup condition provided by perigean spring tides which occur as a protracted, heightened water-level condition coincident with onshore winds has been shown in contemporary accounts of the 1635 coastal flooding event. Under the action of strong, sustained, onshore winds, the previously mentioned backup of water between successive high tides (occurring as a new flood tide comes in before the preceding ebbtide has had an opportunity to recede) provides a natural condition for land flooding. In an actual recorded circumstance more than 325 years later, this fact was clearly substantiated by the great east coast flooding of 1962, whose intervening low tides were built up by sustained onshore winds to become effective high tides (see chapter 7, Case 4).

The preceding 1635 example typifies a case of coastal flooding occurring largely as the result of hurricane-force winds acting upon astronomically augmented tides, which in turn played a very significant role in the extent and severity of the flooding.

In the following treatise dealing with coastal flooding produced by onshore wind effects acting on the higher-than-usual waters of perigean spring tides, primary consideration will be given to those cases of coastal flooding associated with winter storms.

In addition, although meteorologically oriented parameters are duly considered in all examples given, it will be the principal purpose of this volume dealing with perigean spring tides to analyze the astronomical causes contributing to severe coastal flooding. It is these astronomical circumstances forming the principal thesis of this work with which the discerning reader should gradually become familiar. To permit appropriate emphasis on the astronomical forces present, the various factors creating a setup condition of unusually rapidly rising tidal waters, upon which sustained onshore winds act to produce coastal flooding will, therefore, be introduced, one by one, throughout the remaining historical examples. Significantly, these involve, in several cases, a winter storm situation familiarly known today throughout New England as a "nor 'easter."

Because the fundamental astronomical causes for the high tides which lend themselves to coastal flooding are twofold in nature, the circumstances and tide-raising forces resulting from the simple phase alignment of Moon, Earth, and Sun at syzygy will be considered first, followed by a discussion of the combined astronomical perigee-syzygy relationship which adds appreciably to the bimonthly syzygian tide-raising forces. In this historical section—as in part II, throughout the scientific portions of the text—supplementary technical analyses and explanatory footnotes are included for those interested in greater detail.

* * * * *

Technical Commentary

Although the scientific discussion of the cause and effect of perigean spring tides will be reserved for part II, a brief introduction to the phenomenon of perigee-syzygy necessary to an understanding of its flood-producing potential will be included in this present chapter, couched in descriptive terms, and pointing up the relationship with various historical cases of coastal flooding. Such a technical explanation is incorporated in the following 3-page section, supplementing the main text and subordinated in smaller type. The reading continuity of the main text is thereby preserved.

* * * * *

The astronomical tides are produced solely by the gravitational attractions of the Moon and the Sun acting upon large bodies of water. Twice each month, at new and full moon, the Moon and Sun in their respective real and apparent revolutionary motions with respect to the Earth, come into direct alignment with the Earth in celestial longitude (see figs. 1–2). In this relationship, the Moon may either lie along a straight line connecting the Earth and Sun, between the Earth and Sun (at new moon or conjunction) or on the far side of the Earth from the Sun (at full moon or opposition). If, in either case, the Moon simultaneously crosses the plane in which the Earth revolves around the Sun, or comes within a limiting angular distance thereof, a solar or lunar eclipse also must take place. However, these events occur, on the average, far less often.

The alignment of the Sun and Moon with the Earth in celestial longitude occurs twice in each period of 29.53 days. The resulting combination of gravitational forces of the first two bodies creates higher-than-average tides on the Earth. Either of these two positions of alignment between Earth,

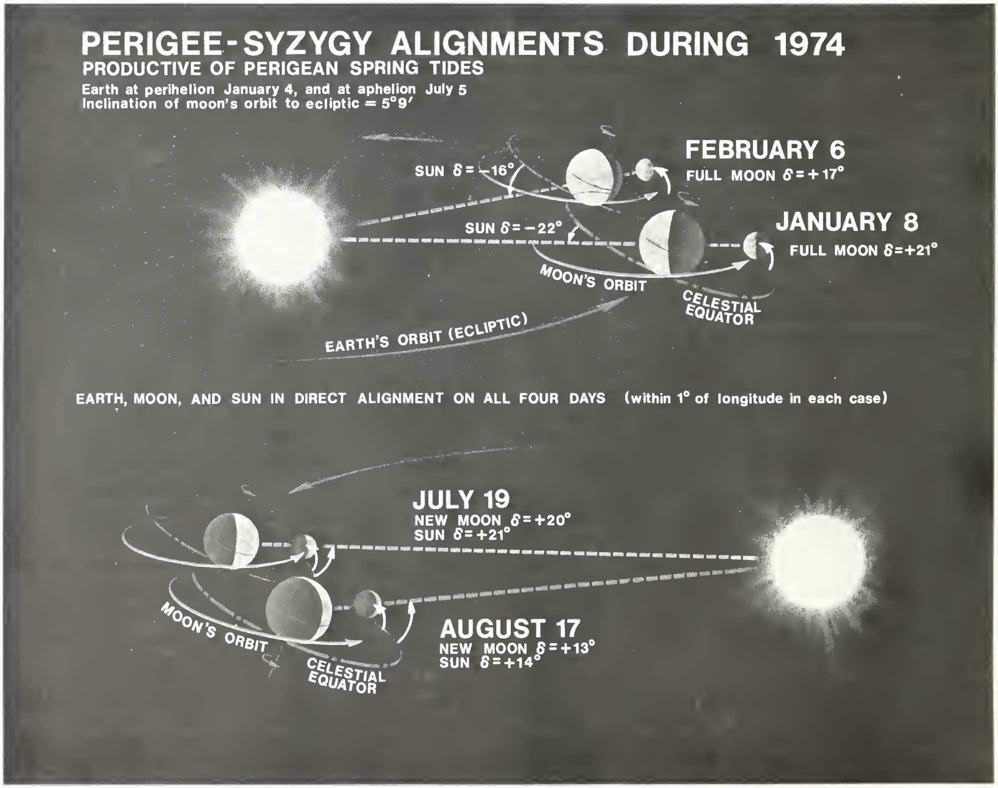

FIGURE 1.—A typical series of close perigee-syzygy alignments occurring in the year 1974. Earth and Moon reach syzygy alignment with the Sun (i.e., at new or full moon) very nearly at the same time the Moon reaches its position of perigee (closest monthly approach to the Earth). The mutually reinforcing gravitational attractions of the Moon and Sun, combined with that of the Moon at its close approach, considerably enhance the tide-raising forces on the Earth's oceans.

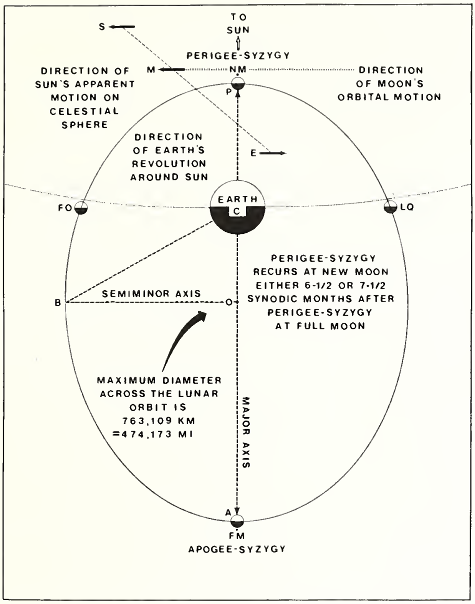

FIGURE 2A.—Syzygy alignment of Moon and Sun at new moon, with the Moon between Earth and Sun. A near-coincidence of perigee and syzygy can also occur at full moon (fig. 2B).

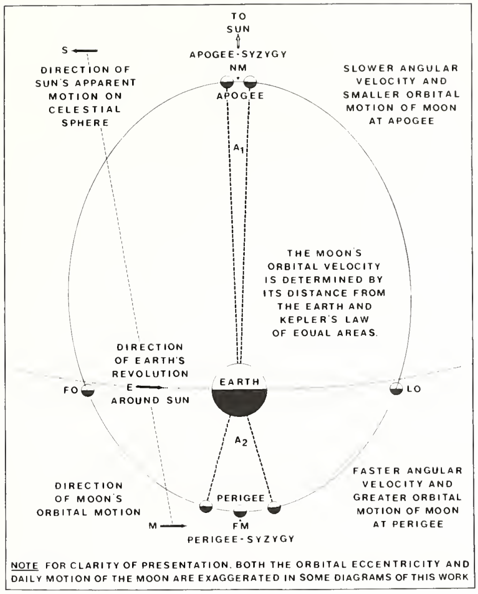

FIGURE 2B.—Revolution of the Moon around the Earth in an ellipse brings it to *perigee* each anomalistic month, averaging 27.555^{d}. It then reaches maximum orbital velocity.

Moon, and Sun in celestial longitude is called *syzygy* (pronounced 'siz-ə-jē) and the increased tides thus produced are called *spring tides* (which refers to their behavior as they "well" or "spring" up—not to the season of the year).

The Moon revolves monthly around the Earth in an orbit which is slightly "out-of-round," or eccentric, with the Earth occupying one of the two foci (*C* in fig. 2A) of the geometric ellipse thus produced, and located slightly to one side of its center, (*O*). At least once a month also (the 27.55-day revolution period can actually allow two occurrences in a calendar month), as the Moon revolves in this elliptical orbit, it reaches its position of closest approach to the Earth, known as *perigee* (*P*).

Generally, the individual phenomena of perigee and syzygy do not coincide in time but, due to numerous approximately commensurable relationships between 29.53 and 27.55, the two events can approach each other within various intervals of close agreement. When this happens, the additional reinforcement of gravitational forces caused by (1) the solar-lunar alignment and (2) the concurrent proximity of the Moon to the Earth produces tides whose high- and low-water phases are even more pronounced than those associated with spring tides. The increased tides thus created are termed *perigean spring tides.*

Much less frequently—on the average not more than once in about one and one-half years—the Moon, which is the greatest single influence on the tides, moves into a perigee position which, as the result of additional dynamic influences diminishing the distance of the Moon from the Earth, lies especially close to the Earth. For purposes of distinction in tidal discussions throughout the present work, such a particularly close perigee position of the Moon with respect to the Earth, hitherto unnamed in astronomy, will be termed a *proxigee,* and the especially amplified type of tide produced as this condition coincides with syzygy will be called a *proxigean spring tide.*

Such especially close (proxigean) distances between the Moon and the Earth always coincide with a very small separation in time between perigee and syzygy. This results (see part II, chapter 3) in a combination and interaction of the gravitational forces of the Sun and Earth in a manner to change slightly and transitorily the shape of the Moon's orbit. Because of a dynamic perturbation in the lunar orbit known as "evection," the Moon at perigee-syzygy draws even closer to the Earth than at its ordinary perigee position and recedes to a greater distance from the Earth at apogee, approximately 2 weeks later. The tide-raising force varies inversely as the cube of the distance between the Earth and the Moon. Accordingly, as a further immediate consequence of this closer approach of the Moon to the Earth at proxigee, increased gravitational forces come into play which, in turn, augment the tide-raising influence exerted by the Moon upon the Earth's major water bodies.

The progressive buildup of these gravitational forces toward an increasingly significant tide-producing role is treated in successive stages in part II, chapters 3–6.

For various reasons, among which are the discrete resonance responses of each individual ocean and portions of these oceans to tide-raising forces, the inertia of the moving water mass, friction with the ocean floor, internal viscosity of the water, and the imposition of continental land masses, the maximum heights attained by perigean spring tides do not always coincide exactly with the times of maximum attainment of the forces which produce them. As will be brought out in later chapters, two of these very important delays are known as the *phase age* and *parallax age*.

These various combinations of astronomical forces acting upon the ocean waters, when taken together with supporting meteorological circumstances, may exert a very practical influence in causing flooding and erosion of, and other damage to, the coastal environment. The associated impact of such coastal zone changes upon human affairs will become increasingly evident throughout part I, chapters 2–4.

If the high-water phase of either the perigean spring or proxigean spring tides occurs while a strong, persistent, onshore wind is blowing (fig. 3), a major coastal flood in low-lying areas is almost inevitable. A nonfrozen condition of the surface waters in large bays or the near-shore region is, of course, assumed in this connection. It has been found that over 100 cases of major coastal flooding associated with these conditions have occurred on the North American coastline in the past 341 years. Such a strong, sustained, *onshore* wind, which tends to pile up the waters along the coast and enhance the effect of the already high, astronomically produced tides, is an essential ingredient for coastal flooding.

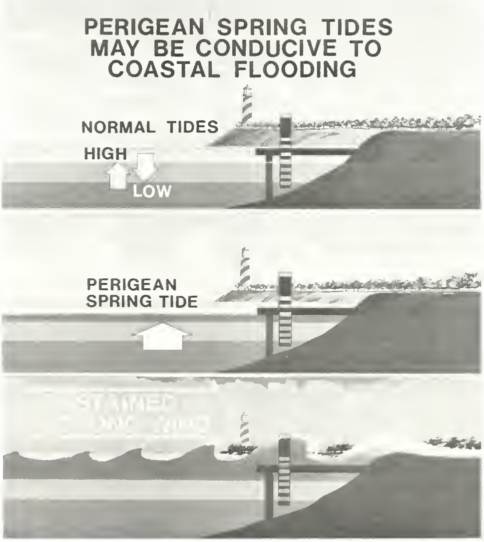

FIGURE 3.—Strong, persistent, onshore winds may create tidal flooding on low coasts, as friction between wind and sea lifts amplified perigean spring tides onto the land.

Conversely, a continuous, strong, *offshore* wind tends to lower the tidal water level and to negate the effects of a perigean spring tide. The atmosphere and the ocean act together like an inverted barometer. As the atmospheric pressure rises, the water level goes down; as the atmospheric pressure diminishes, the water level rises. The adjustment in ocean level in either direction is approximately 13 inches for each change of 1 inch in barometric pressure.

Only lowland coastal regions and those with a sufficiently large daily range between high and low phases of the tide are subject to the flooding effects noted. (The combined conditions of perigee-syzygy add about 40 percent to the tidal range.) Thus, the entire coast of the Gulf of Mexico and much of the southeastern coast of the United States are excluded from this particular influence, except during hurricanes. Hurricanes possess sufficient wind velocity to lift even relatively shallow waters onto the land. As a result of the continuous frictional effects made possible by the large-scale movement of wind over the surface of the water (the lateral extent of this overwater wind movement is known as the "fetch"), a hurricane passing even well off the coast and producing a strong swell which impacts a low shoreline can cause coastal flooding.

In the case of the coastal storm system of August 24–26, 1635, it is difficult because of the ensuing lapse of time—and lacking either manuscript or published weather data—to know whether this system persisted as a true tropical storm originating from energy provided by warm tropical waters, or was partially modified by a contrast of atmospheric air masses in extratropical latitudes. While seemingly maintaining—as indicated in the several descriptive accounts available—its basic identity as a true hurricane, nevertheless at this high latitude of occurrence it may possibly have taken on some of the characteristics of an extratropical storm, such as were instrumentally recorded and plotted on the synoptic weather map, 303 years later, during the great New England hurricane of September 21, 1938.[5]

This hurricane began as a tropical storm of comparable intensity and possessed a similar northward movement along the Atlantic coast to New England, accompanied by strong, onshore winds. It was separated by 1 day from the mean epoch of an only approximate perigee-syzygy situation. The corresponding separation between perigee and syzygy was −69 hours. The flood waters raised at Providence, R.I., in this instance were 18.3 ft above mean low water, compared with approximately 20 ft at the closer perigee-syzygy alignment accompanying the storm of August 24–26, 1635.

* * * * *

Case No. 4—*Perigean (Proxigean) Spring Tides* ($\pi = 61'27.0''$, $P - S = -6^h$)

At approximately 7 o'clock in the evening, 75°W.-meridian time, on Saturday, February 23, 1722/23 O.S. [March 6, 1723] the Moon in its monthly revolution around the Earth reached a position of direct alignment with the Sun in the angular reference system known in astronomy as celestial longitude.[c] The result was the familiar phenomenon of new moon,[d] which happens once each month and is of no unusual consequence. As an astronomical occurrence which preceded this one by only 6 hours on the same date, the Moon also passed through its position of closest monthly approach to the Earth, known as perigee—again a regular monthly happening, and by itself of no special significance. However, the near-coincidence of new moon and perigee is of particular significance. In the combination of these two events, a far less common astronomical circumstance occurred, which was made the more meaningful by the simultaneous, unusually close proximity of the Moon to the Earth.

In the orderly astronomical cycle of events which govern and alter both the distances and motions of the Moon, such a condition of close agreement between the time of the closest monthly approach of the Moon to the Earth (perigee) and the alignment of Earth, Moon, and Sun responsible for the production of a new moon or full moon (either alignment being called *syzygy*) is termed, appropriately, *perigee-syzygy*. The resulting forces created are manifest by their action in producing, within the Earth's tidal waters, the phenomenon of *perigean spring tides*.

On the east coast of the United States, the normal lag time between the occurrence of such a combined astronomical event and the resulting perigean spring tides produced is approximately 1 to 1½ days. As it happens, therefore, the force-amplified perigean spring tides which occurred, on February 24 (Old Style Calendar), 1722/23, one day after the perigee-syzygy date of February 23, very nearly coincided with the arrival of a very strong coastal storm on the east coast of New England. This storm—although of extratropical origin (i.e., formed outside of the normal tropical region of hurricanes)—rapidly approached the wind velocities associated with such a tropical disturbance and sent strong, sustained, onshore winds lashing for many hours against the coastlines of Massachusetts and New Hampshire. The ensuing catastrophe was described, in the somewhat colorful language of the period, in a report by the contemporary American cleric-scientist-philosopher, Cotton Mather, to the Royal Society of London:

". . . It was Feb 24, 1723, when our American philosophers observed an uncommon concurrence of all those causes which a high tide was to be expected from. The moon was then at the change, and both sun and moon together on the meridian. The moon was in her perigee, and the sun was near to his having past, [i.e., the closest distance between moon and sun, occurring about January 4] . . . finally the wind was high and blew hard and long . . . Then veering eastwardly it brought the eastern seas almost upon them [these shores] . . . They raised the tide unto a height which had never been seen in the memory of man among us . . . The City of Boston particularly suffered from its incredible mischiefs and losses . . ." [6]

It is significant that without actually being given the name perigee-syzygy, all of the requisite conditions for a close occurrence of this phenomenon were present: ". . . moon was then at the change (new phase); . . . moon was then in her perigee; . . . sun was near to his having past."

The *Boston News-Letter* of that time reported that

". . . the inundation in Boston looked very dread-

[c] Definitions of many of the astronomical and tidal terms used in this publication will be found in the appendix and in part II, chapter 1. To avoid any ambiguity in meaning possible through overgeneralization, extreme caution must be exercised in the exact specification of terminology even in this nontechnical introduction. Thus, for the phenomena of new moon or full moon to occur, only the *celestial longitudes* of the Moon and Sun need be the same.

However, if, at the time of full moon, the Moon's longitude is between 9°30′ and 12°15′ of one of the two positions (the so-called "nodes") where, twice each month, the Moon crosses the orbital path of the Earth around the Sun (the "ecliptic") the Moon will also be aligned (within the diameter of its disc) with the Earth and Sun in *celestial latitude* and a total lunar eclipse will occur.

Similarly, at new moon, if the Moon is within 9°55′ and 11°50′ of one of these same nodes, a central (total) eclipse of the Sun will take place—or, if the Moon is then beyond a certain limiting distance from the Earth, an annular eclipse of the Sun will result. As indicated earlier, a total eclipse of the Moon followed within 2 days of the August 24–26, 1635 coastal flooding event. The conditions of this eclipse resulted in a faster apparent motion of the Moon, a shorter (relative) duration of the eclipse, and a greater duration of the lunar and tidal days (see chapter 6) in addition to more closely aligned tidal forces of the Moon and Sun.

[d] As previously noted, such an alignment in longitude (or, alternatively, right ascension) between Sun, Earth, and Moon at either new moon (conjunction) or full moon (opposition) is known in astronomy as syzygy (from the Greek *syn* "together" and *zygon*, "yoke"). At conjunction, lost in the glare of the Sun's rays, the new moon is actually invisible to the eye; too often, people associate the slim crescent appearing immediately before or after the new moon with this descriptive term.

ful . . . the tide rising to a height of 16 ft . . . At Hampton, New Hampshire, the storm caused the great waves of the full sea to break over its natural banks for miles together, and the ocean continued to pour its water over them for several hours." [7]

With the causes of such coastal flooding now firmly established, additional important historical examples will be considered in terms of their effects only, without explanatory comments.

* * * * *

Case No. 7—*Perigean Spring Tides* ($P-S=-17^h$)

A similar severe coastal storm struck Boston and New England on December 4–5 (New Style), 1786. Strong onshore winds again acted upon perigean spring tides resulting from the combination of a lunar perigee reached at 2 p.m. in the afternoon of the 4th, local time, and a full moon occurring 18 hours later.

As reported in *The Boston Gazette and The Country Journal* for December 11, 1786:

". . . The wind at east, and northeast, blew exceeding heavy, and drove in the tides with such violence on Tuesday, as overflowed the pier several inches, which entering the stores on the lowest parts thereof, did much damage to the sugars, salt, etc. therein—considerable quantities of wood, lumber, etc., were carried off the several wharfs . . ." [8]

This great coastal storm, which became known as the December Gale of 1786—with its associated tidal flooding—also was accompanied by subfreezing conditions, and left a 5–6 ft snowfall throughout New England. As the direct cause of numerous cases of drownings and shipwrecks, it was long remembered as one of New England's worst tidal flooding disasters.[9]

* * * * *

Case No. 8—*Perigean Spring Tides* ($P-S=+10^h$)

Perigean spring tides produced under similar circumstances (a perigee-syzygy configuration centered around 2 p.m. in the afternoon, local time, on March 24) reached their peak on March 25, 1830. Their flooding potential became manifest the next day when:

"A cold, northeast storm of wind, rain and snow raged along the coast of New England . . . producing a great tide, which in some parts exceeded the highest tide remembered there. The storm began on the morning of Friday, the twenty-sixth, and continued till one o'clock in the afternoon, the tide being at its height at noon of that day.

"At Portland, Me., several wharves were carried away, and many vessels lost their fastenings, some being driven on shore and others greatly damaged by being beaten against the wharves . . .

"At Portsmouth, N.H. wharves were injured and several vessels driven ashore . . .

"At Gloucester the water was two or three feet deep on the wharves, and much movable property was washed away, the waves being covered with articles and debris of all kinds . . .

"The tide rose at Boston one and one-half inches higher than the great tide of December, 1786, which was ten inches higher than the highest that any person then living remembered. The water broke through the dam along the Roxbury canal . . . sweeping away fences and outhouses, and prostrating buildings.

"Much property was set afloat at Charlestown and Cambridgeport. The navy yard was overflowed, and the tide broke through the coffer-dam, about three feet of water coming into the dry dock." [10]

* * * * *

Case No. 13—*Pseudo-Perigean Spring Tides* ($P-S=-53^h$)

Between the 14th and 16th of April 1851, a severe case of tidal flooding occurred as a result of an event which has come to be known as the "Minot's Light Storm"—since this famous lighthouse of Boston's Outer Harbor was temporarily destroyed as a result. The associated tidal contribution to coastal flooding provides an example of a type later to be described in this volume as a pseudo-perigean spring tide (i.e., having characteristics generally similar to, but—for lack of an equal gravitational force acting—not precisely the same as, those of a perigean spring tide). In this case, the two elements concerned, perigee and syzygy, were more than 36 hours, but less than 84 hours apart—the arbitrary limits set as a terminology standard throughout this case study.

With perigee occurring at 1 o'clock in the afternoon (local time) of April 13 and full moon at 6 p.m. on the 15th, the gravitational forces of Moon and Sun were not united to the fullest possible extent as when these conditions occur within less than a day of each other. However, coupled with a strong, sustained, onshore gale—one of the severest of the century—the tidal flooding potential became extremely high. A vivid account of the disaster has been given in Sidney Perley's book, *Historic Storms of New England:*

"It [the storm] commenced at Washington, D.C. on Sunday [the 13th], reached New York Monday morning, and during the day extended over New England . . . The Moon was at its full, and the water having been blown in upon the shores for several days the tide rose to a greater height in many places than was remembered by the people then living. It swept the wharves and lower streets like a flood, and at Dorchester, Mass., rose nearly seven feet higher than the average tide . . .

"On all parts of the coast where the northeast wind could exert its force the tide rose over the wharves from one to four feet. At Provincetown, on Cape Cod, many wharves and salt mills were swept away; and in several places people left their houses, which were flooded, water being six inches on the lower floors in some of them.

"At Boston [where the tide averaged 15.62 feet] the water was three or four feet deep on Central and Long wharfs, and the wooden stores on the latter wharf were completely inundated . . .

"Deer Island in Boston harbor suffered extensively by the great tide which made a complete breach over the island, covering nearly the whole of it. The sea-wall that had been built there a few years before by the government was washed away; and three buildings were carried out to sea, one of them being the school-house . . ." [11]

Excerpted and abridged, in part, from Edward Rowe Snow's work on *Great Storms and Famous Shipwrecks of the New England Coast,* and somewhat rearranged in terms of the importance of the tidal disaster involved, is the following description of this catastrophe:

"The City of Boston actually became an island during the Wednesday high tide as the water swept across the neck, cutting the city off from the mainland completely. On Harrison Avenue the water was four feet deep, and the tide flowed entirely across Washington Street near the corner of Waltham Street. In downtown Boston the waves swept right up State Street, with the area around the Custom House three feet under water . . . Brown Street was partially submerged, the waves continuing up Central and Milk Streets. It is said that Merchants Row was reached by the great tide. The record high tide submerged both the Charlestown and Chelsea bridges . . . on Pleasant Beach in Cohasset . . . a large three-story hotel was floated right out from its underpinning, with almost a score of guests escaping in time . . . The tide at Dorchester, Mass., rose seven feet higher than usual. . . The boys at Deer Island school . . . were caught in their dormitory with the water steadily rising around them. . . By midnight the water had risen to a height of five feet, and the roof of the building fell in. . . Derby Wharf in Salem was ruined. The railroad track at Collin's Cove and the bridge between Forrester Street and Northey's Point were carried away, and the sea rushed into the tunnel. In Beverly the sea washed over Tuck's Point and over Water Street, while the tide in Gloucester was said to have been the highest in fifty years. . . The passage through Shirley Gut was widened to twice its former size. . . The storm raged all along the coast from New York to Portland, Me. The feeling was general that the storm brought a higher tide and greater gale than any since December 1786. . . Damage to shipping was estimated in hundreds of thousands of dollars, while property all along the coast was destroyed. . ." [12]

* * * * *

Case No. 36—*Near-Ordinary Spring Tides*

An ordinary spring tide situation in which a moderate 3½-day proximity to the time of perigee set up an additional potential for tidal flooding occurred on the morning of December 26, 1909, in connection with the so-called "Christmas Gale" of that year. Full moon occurred at 4:30 in the afternoon on December 26, preceded by perigee at about 4:00 a.m. on December 23, local time, a difference of 84½ hours. This is marginal to the maximum separation-interval adopted for a pseudo-perigean spring tide (84 hours)—but the associated tidal flooding took place only some 36 hours from the mean time between perigee and syzygy, computed to be approximately 10:00 p.m. on December 24. As will be discussed in note,[†] table 1, even such a 3½-day proximity between the time of perigee and the time of syzygy (or, more meaningfully, the occurence of a spring tide within 1½ days of the mean epoch, or average time between perigee and syzygy) can reinforce, and provide a definite amplitude contribution to, an ordinary spring tide.

In every sense of the word, therefore, the spring tide must be regarded as the basic higher-than-usual high tide, to which the effects of a near-coincidence between perigee and syzygy are added. The concept of perigean tides standing alone without any contribution from syzygy can only be realized once in any given lunation and during certain nonconsecutive months, when the Moon is simultaneously at perigee and quadrature. The concept of syzygian (spring) tides standing alone without sensible reinforcement from perigee, on the other hand, is valid on twice as many occasions throughout an extended period of time—viz., at those apogee-syzygy positions occurring at either new or full moon.

The ordinary spring tide is, therefore, more logically the comparative standard for a greater-than-average high tide, upon which the effects of perigee-syzygy are additionally superimposed—rather than the effects of a syzygian tide being thought of as impressed upon those of a perigean tide.

The present case of tidal flooding is an example of the sea surface being raised to comparatively high levels by the joint action of winds and tides (either of which is subject to varying intensities and amplitudes)—a fundamental principle that will be enunciated many times in the present volume.

As reported in the *Monthly Weather Review* for January 1910:

"The morning tide of December 26, 1909, attending the severe storm of this date on the New England coast, was one of the highest ever recorded in Boston Harbor. . .

"At Boston Light the predicted time of high tide was 10:20 a.m. The wind from the later afternoon of the 25th until nearly noon of the 26th was from the east and northeast over Boston Harbor and Massachusetts Bay, rapidly increasing in force during the evening of the 25th to very high velocities soon after midnight, which continued undiminished through the morning and day of the 26th. At Cape Cod, Highland Light, the velocity at 8 a.m. of the 26th was 48 miles, northeast [the wind velocities stated are uncorrected values—not adjusted for instrumental error; corrected values are about three-fourths of the values given]; noon, 72 miles; 2:15 p.m., 84 miles; at 5 p.m., 66 miles—all from the east-northeast—and at midnight was 60 miles, north. At Boston the hourly movements from midnight to noon of the 26th ranged between 25 and 39 miles, the hourly maximum rates between 32 and 45 mph—the latter occurring at 5:10 a.m., from the northeast. . .

"The increasing and high wind, occurring with the rising tide, together with a high run of tide, caused the water in Boston Harbor to reach approximately the record height of the tide of April 14, 1851 (The Lighthouse Storm), which at the U.S. Navy Yard was 15.0 to 15.1 ft—the height of the tide of December 26, 1909, being, at the same station, 14.98 ft. In general the tide in Boston Harbor and Massachusetts Bay was approximately 3.5 feet above the predicted height. The actual height as given by the U.S. Engineers and other reliable authorities at the following places was as follows: Newburyport, Massachusetts Harbor, Black Rock Wharf, 12.68′; Sand Bay, Rockport Harbor, 13.64′; Boston Harbor, Deer Island, 14.56′; Plymouth Harbor, 14.8′; Barnstable Bay, 13.25′; Provincetown Harbor, 14.35′; the tide at all these stations with the exception of Plymouth and Barnstable was approximately 5 feet above mean high water." [13]

* * * * *

Coastal Flooding As an Ongoing Risk

The detailed case-study forming a part of the present research effort shows that the phenomenon of perigee occurring either in near-coincidence with, or comparatively close proximity to (i.e., within even several days of), new moon or full moon, has reinforced spring tides on many occasions and in varying degrees down through history. Also, in repeated examples throughout history, perigean spring tides, combined with intense onshore winds, have provided an important source of coastal flooding.

Subsequent technical discussions will include an evaluation of the increased flood-producing potential of hurricanes which occur at the same time as perigean spring tides. A proposed intensity scale also will be developed to indicate the comparative degrees of coastal flooding possible from various intensities of onshore wind combined with the separate categories of (1) proxigean spring tides, (2) perigean spring tides, (3) pseudo-perigean spring tides, and (4) ordinary spring tides. In the light of this intensity grouping by classes, the foregoing examples (in addition to their historical significance) have been chosen as being representative of each of these four types of astronomically augmented tides. A more meaningful expansion from these few introductory cases is now desirable.

Table 1 contains a list of 100 representative examples of major tidal flooding occurring along the North American coastlines between 1683 and 1976, associated with the near-simultaneous occurrence of perigean spring tides (as a generic term) and strong, sustained, onshore winds. This list includes, and distinguishes between, cases of proxigean spring, perigean spring, and pseudo-perigean spring tides according to the nomenclatural definitions given in table 22 and the accompanying text.

Other representative cases in which landfalling hurricanes have provided a source of intense winds, resulting in severe coastal inundation in addition to wind damage (and a greater degree of flooding than is experienced in hurricanes occurring at other times than perigee-syzygy) are contained in table 2.

Surface synoptic weather maps are included in part II, chapter 7, to match more than 25 cases of tidal flooding. These graphically portray the condition of coastal weather and distribution of the wind pattern at the time the flooding occurred. Because of total space limitations, these examples were chosen at random from the master lists, but include one case in each decade from 1890 to 1970, distributed in latitude from Halifax, Nova Scotia, to Long Beach, Calif., on both the east and west coasts of North America (representing both semidiurnal and mixed tides), in all months from October through April (and with perigee-syzygy separations from ±1 to −34 hours. Numerous illustrations of the destructive effects of such coastal flooding incidents are also interspersed throughout the latter portions of the text.

In this wealth of available previous examples, there is a pattern of recurring significance. On both the Atlantic and Pacific shorelines of the United States, wherever lowland coastal regions exist, perigean spring tides coupled with strong, sustained, onshore winds become an all too frequent harbinger of tidal flooding. On the east coast of Florida, along the coast of the Gulf of Mexico, and at certain other specific coastal locations, as will be seen in part II, chapter 8, limited daily tidal ranges greatly reduce the attendant hazard of tidal flooding except in the case of hurricanes.

The most outstanding 20th century example of coastal flooding associated with perigean spring tides, which occurred on March 6–7, 1962, will be discussed at length in part II, chapter 7. The more recent tidal floodings, of January 8, 1974 along the southwest coast of California and—allowing for the appropriate tidal delays—2 to 3 days later along the southwest coasts of England and Wales and on the Islands of Guernsey and Lewis, also will be treated separately in this chapter. Satellite weather photographs revealing offshore cloudcover by day and night (infrared) indicate the frontal and weather patterns that existed during these 1974 incidents of tidal flooding.

A further group of cases of coastal flooding which have occurred at times of ordinary spring tides, supported by the necessary wind velocities and varying degrees of proximity to perigee, are listed in table 3.

Numerous additional instances of the highest tides of record at various coastal localities are given in table 4. These particular cases were all observed at times of perigee-syzygy, but lacked the simultaneous existence of sufficiently high or sustained onshore winds to cause noticeable flooding.

A system of scientific controls also has been implemented (see table 27 and figs. 70–89), suitable for the analysis of certain cases of strongly potential tidal flooding which failed to materialize. All such cases were associated with a close perigee-syzygy alignment and other astronomical tide-raising factors which, although they lifted the water to unusual levels, did not produce flooding. In this control system, an equal number of representative examples has been included for a wide variety of dates and circumstances agreeing in statistical randomness with the cases of active flooding (table 1) in order to provide statistical comparability therewith. As an acid test of principles to be developed in part II, chapters 3–6, they, like the first group of cases, possess properties rendering them especially vulnerable to tidal flooding which, paradoxically, did not occur.

As a first and most important consideration, these examples have been chosen on the basis of an extremely small difference between the times of perigee and syzygy (less than 1 to a maximum of 12 hours). Secondly, each has been selected as possessing one or more special features which, in terms of the exceptionally high tides produced thereby, should make the situation one extremely susceptible to tidal flooding.

Among these conditions occurring either singly or in combination and contributing in various degrees to the production of exceptionally high tides are: (1) an unusually large value of the lunar parallax, indicating an exceptionally close approach of the Moon to the Earth; (2) the location of the Moon directly in the zenith (i.e., at altitude=90°); (3) the position of the Sun very close to solar perigee (around January 1–4 of the year); (4) the location of the Moon very near to the vernal or autumnal equinox, around March 21 or September 23, respectively, thus being on the Equator and aligned with the Sun in both declination and celestial longitude; (5) the location of the Moon at, or very near to, one of its nodes (positions of crossing the ecliptic) at the same time the Sun is near this same longitude, resulting in a solar eclipse (at new moon) or a lunar eclipse (at full moon); (6) the new moon being simultaneously at the same high declination, or the full moon at an opposite high declination (in algebraic sign) with the Sun, causing a force alignment in declination as well as an increase in the tidal day; and (7) the presence of the Sun at the summer or winter solstice (greatest annual declination), increasing its apparent motion in right ascension, and lengthening the tidal day in the same manner as a high declination of the Moon. These various effects will be completely described in part II, chapters 1–4.

With such very favorable astronomical conditions adding their individual effects to that of the perigean spring tide already present, the immediate question from the standpoint of the premise subsequently advanced (calling for a strong tidal flooding potential under these conditions) is why no reported tidal flooding actually occurred. And here again a very definite emphasis must be placed upon the necessity that the two natural forces—astronomical and meteorological—work together in close unison if tidal flooding is to occur.

Neither a powerful offshore winter storm nor an exceptionally uplifted astronomical high tide—one without the other—can produce the devastating flooding effects abundantly illustrated among the many cases resulting from the combination of these factors documented in table 5. The considerably augmented astronomical high tide resulting from the condition of perigee-syzygy, which will be discussed extensively in the ensuing chapters—often supported by additional astronomical factors such as those listed above—provides the setup condition for subsequent wind action. An active coupling between strong, sustained, onshore winds, if present, and the surface of the sea provides the second factor necessary to cause active coastal flooding.

The absence of flooding in these control cases is clearly shown by the accompanying weather maps to be due to high atmospheric pressure and a condition of calm—or offshore (rather than onshore) winds along the coast, acting to negate the effect of the astronomically induced high tides.

The action of negative (depressed) tides produced by intense *offshore* winds during the low-water stage of perigean spring tides is also duly considered on pages 93, 103, in terms of the threat for ship groundings and strandings.

As a followup to the cases of tidal flooding listed in the tables of this chapter, and as an indication of the continuing, open-ended relationship of this historical overview, facsimile copies of newspaper articles describing tidal floodings which have occurred widely along the North American coastlines are included, in chronological order, on the following pages (table 5). These serve to summarize, from an at-once historical and yet contemporary, firsthand point of view, the effects of a quite considerable number of cases of coastal flooding resulting from the coincidence of sustained, onshore winds and perigean spring tides over a period in history covering the 18th, 19th, and early 20th centuries. Appropriate data for each occurrence are contained in the accompanying captions. The events reported speak for themselves in the intensity of the tidal flooding damage sustained.

From the standpoint of the contribution made to such events by perigean spring tides, certain of these cases of coastal flooding will be further individually evaluated in part II, chapter 7. The gradual reduction in the frequency of reported cases of severe tidal flooding in more recent years, as the result of an increased construction of seawalls, breakwaters, groins, and other devices designed to prevent coastal flooding, will also be given appropriate attention in this later chapter.

In connection with these reproduced news articles from a fairly extensive range of coastal communities, and covering a span of 251 years, several pertinent comments are in order:

Both in the case of very early newspaper accounts and those published in relatively small coastal communities, it is necessary to consider that most of the newspapers involved are weeklies. Accordingly, the reporting time of a coastal storm accompanied by tidal flooding which occurred just prior to a weekly publication date and too late for inclusion at that time may be delayed as much as a week.

It must also be remembered that, in the documentation of such tidal floodings, the news value of these natural events as determined by the news editor is at all times in competition with other news of the day, of political, international, economic, or other topical interest. The timing of the flooding in relation to press deadlines and follow-on editions, as well as the writing skills, thoroughness, and even the working habits of the reporter can all affect the degree of prominence given to one story compared with another whose flooding consequences are ostensibly as great. A lack of technical knowledge on the part of the reporter, a desire to achieve a sensational story, or an excessive shortening of the article by a news editor—all can affect the accuracy of the pertinent data. Any quantitative comparison and analysis made from newspaper accounts is, therefore, subject to some degree of qualification in keeping with these considerations.

In conclusion, a brief explanation is desirable concerning the examples of tidal flooding cited in different chapters of this work.

Methods of Identification and Evaluation of Representative Cases of Tidal Flooding

The 100 representative cases of coastal flooding associated with perigean spring tides which are listed in table 1 are chronologically arranged and numbered for convenience in reference. In order to provide for a greater variety in the case-study analysis used in different portions of the text—as permissible within space limitations—the cases variously chosen from among the 100 for individual evaluation are not always the same. However, a common thread of comparison has been maintained by including data for a single, consistent group of cases throughout the volume.

To permit a ready means of correlation between such related sets of data covering various aspects and influences of perigean spring tides in different chapters of the text, an alphanumeric system of identifying these common cases has been adopted. The several randomly selected listings of perigean spring tides (distributed widely in time and geography, and both accompanied and unaccompanied by tidal flooding) which have been mentioned earlier in this section constitute control groups. Each of the events in these individual groupings carries the same identifying number, allocated in chronological order, given to it in the first columns of tables 1–4. In addition, for those cases which appear repeatedly among the tide curves, weather maps, newspaper articles, etc., published throughout the volume, a key letter has been assigned.

The keying letter and/or number serve to identify a flooding or nonflooding situation as the same tidal circumstance, no matter where it appears in the text, without reference to the accompanying date. In some cases this is a weather map date (usually the same as the date of tidal flooding), in others, it is the date of the published newspaper article (often a day or so later) relating to the tidal flooding, and in still others represents the mean epoch of perigee-syzygy. Wherever a numerical or alphanumerical designation is given in the caption accompanying graphical or tabular material, these data form a correlatable set with any similarly labeled perigee-syzygy data appearing elsewhere in the volume.

Due care should be exercised in making all intercomparisons to check the standard time zone for which the data apply. Most of the synoptic weather map, coastal flooding, or related tide table data are given either for the time meridian of 75° W. (eastern standard time) or 120° W. (Pacific standard time)—depending, in the last two instances, on the coastline involved.

All astronomical and ephemeris data relating to the Sun, Earth, or Moon (including the computer printouts) are referred to ephemeris time (e.t.)[e]. First adopted internationally for use starting in 1960, and based upon the comparison of exact lunar observations with gravitational data rather than upon the rotation of the Earth, as heretofore, ephemeris time is the modern form—with some small distinctions and corrections—of Greenwich civil time. Between January 1, 1939 and January 1, 1960, astronomical data were given in universal time (u.t.), otherwise known as world time or Weltzeit (W.z.), temps universel (t.u.), or Greenwich zone time (Z)—all of which are equivalent to Greenwich civil time (G.c.t.). In each case, 24 hours constitute the day, starting at midnight (0000^h) and lasting until the next midnight (2400^h). Universal time is still used instead of ephemeris time in astronomical applications other than those that relate to the Sun, Moon, and planets, and likewise always refers to an astronomical day starting at Greenwich midnight, no matter in what year it occurs.

[e] This abbreviation should not be confused with that for eastern standard time (e.s.t.) also used in the text.

However, several possible pitfalls exist in the comparison of the times of tidal flooding events taking place in different years, particularly in the past: (1) Prior to January 1, 1925, Greenwich mean time (G.m.t.) was used, in which the 24-hour day began at Greenwich mean noon, rather than the preceding midnight. Although Greenwich civil time came into use in the 1925 issue of *The American Ephemeris and Nautical Almanac,* the designation universal time did not appear until the 1939 edition. In converting to Greenwich civil time or universal time, 12 hours always have to be added to Greenwich mean time; (2) The term Greenwich mean time (but reckoned from Greenwich midnight) also continued in use in the British *Nautical Almanac* during the same period that Greenwich civil time was being used in *The American Ephemeris and Nautical Almanac* and before they both converted to universal time and then ephemeris time; and (3) The designation Greenwich mean time is still used today in the navigational and tide publications of some English-speaking countries. Although this otherwise abandoned nomenclatural usage implies a time 12 hours earlier, it pertains to a value which is intended to be the same as universal time or Greenwich civil time, starting at Greenwich midnight.

To avoid confusion with the similarly named Greenwich mean time which had been used in the United States before January 1, 1925, the more complete designation of Greenwich mean astronomical time should be assigned to any reckoning system which is based upon Greenwich mean noon. In early editions of *The American Ephemeris and Nautical Almanac,* the meridian of Washington D.C., was also used for various astronomical position and time determinations, and the exact designation of this meridian has undergone several changes over the years.

The lengths of all days (solar or lunar) specified throughout the text are given in terms of their equivalents in mean solar time (1 mean solar day = 1,440 mean solar minutes = 86,400 mean solar seconds), based on the fictitious motion of the mean Sun.

Reference should also be made to the note in connection with Julian (Old Style) and Gregorian (New Style) calendars on page 1.

Remarks Concerning the Fundamental Astronomical, Tidal, and Meteorological Data Sources Used in Connection With Computations for this Volume

The times of perigee and szyygy, the separation-interval between them, and the mean epoch of this combined phenomenon are given for each case of tidal flooding listed in tables 1, 2. In the reductions leading to these tabulations, as elsewhere throughout the volume, the data contained in the computer printout of table 16 have been used, for consistency, in all instances where $P-S \geq \pm 1 \leq \pm 24$ hours. An arbitrary interval of one mean solar day has been set as the separation limit between perigee and syzygy for all cases of perigee-syzygy "alignment" appearing in this latter table.

Within this ±24-hour limitation, table 16 (compiled from magnetic tape data by the U.S. Naval Observatory) provides the means for extending such perigee-syzygy data backward in time to historical dates even prior to the existence of published nautical almanacs and astronomical ephemerides. Among the earliest of such published data sources, the French *Connaissance des Temps* was first issued in 1679, the British *Nautical Almanac* in 1767, the Italian *Effemeridi astronomiche* (original Latin title *Effemeridi astronomicae*) in 1775, the German *Berliner astronomisches Jahrbuch* in 1776, and *The American Ephemeris and Nautical Almanac* in 1855.

Where the $P-S$ separation-interval is greater than ±24 hours, the corresponding data have been obtained from these astronomical ephemerides, within their dates of availability. For earlier dates, these data have been calculated retroactively on the computer, resorting to the same analytical approach involving the application of periodic terms and coefficients in the solution of the lunar disturbing function which is used in the compilation of table 16.

Table 16 is prepared from computer-programmed equations and theoretical methods of analysis which differ, for example, from the standard interpolation method for determining the times of perigees from maximum values of the parallax, used in *The American Ephemeris and Nautical Almanac* and other ephemerides. Rounding-off procedures involving data truncation to the nearest significant figure also have been employed in the computer printouts.

As a result, variations of up to one-half hour may exist between corresponding values obtained by the several methods noted above (or, if the rounding-off errors add in the same direction, differences of up to 1 hour may occasionally result). These variations are the most critical when $P-S$ is very small, and the solar perturbation of the lunar line of apsides is, correspondingly, at its greatest value. However, the maximum influence of the strong, onshore surface winds required to produce coastal flooding in connection with perigean spring tides usually extends over at least several hours. The influences of phase and parallax ages, variable with location, also affect the interval between the occurrence of perigee-syzygy and the production of the maximum perigean spring tides. Such small differences possible in the mean time of perigee-syzygy are, therefore, not detrimental to the accuracy of the present study.

In this same connection, a greater uncertainty exists in determining the exact time of perigee than in the case of syzygy, and the former value is now customarily given only to the nearest hour, whereas the time of syzygy is given to the nearest minute. Carried to the accuracy of the less well-known component of the pair, the value of the mean epoch of perigee-syzygy is rounded off throughout this book to the nearest hour only, or—where odd-value separation-intervals are involved—to the nearest half-hour. One exception to this procedure exists: In order to separate and emphasize the effects of particularly close perigee-syzygy alignments, where the difference $P-S \leq \pm 1^h$, its precise value has been computed, in minutes of time, directly from the data in an astronomical ephemeris.

* * * * *

Of significance to certain tables contained in later chapters of this study are the earliest years in which (1) formalized tide data were available, and (2) synoptic weather maps were issued in the United States.

Between 1853 and 1867, the first rudimentary tide tables resulting from studies made at certain larger seaports on the east coast of the United States were contained among the text and appendixes of the annual *Reports of the Superintendent of the Coast Survey.* These consisted, for the most part, of related tidal data requiring further self-computation and use by the navigator.

In 1867, the actual prediction of high tides for 15 stations on the east coast of the United States was begun.

Because of the special demands made necessary for safe navigation over shoals, bars, and reefs, the prediction of daily low waters for the west coast of Florida as well as for the Pacific coast of the continent was begun in 1868. In 1887, the prediction of both high and low waters for 16 stations on the east coast also was inaugurated.

In 1885, the use of the first tide-computing machine in the United States, devised by William Ferrel of the U.S. Coast and Geodetic Survey and utilizing 19 harmonic constants, was instituted. In 1896, such tidal predictions were extended to include 70 standard reference stations throughout the world, together with tidal differences for an additional 3,000 stations.

In 1912, annual tide tables were computed for the first time by USC&GS tide-predicting machine No. 2 (developed by Rollin A. Harris and E. G. Fischer of this organization in 1910, and utilizing 37 harmonic constituents).

Beginning with the tide tables for 1966, the use of an electronic computer was introduced, by which all tide predictions published by the National Oceanic and Atmospheric Administration/National Ocean Survey are now calculated.

* * * * *

In connection with the availability of various meteorological sources cited in part II, chapter 7, the first issue of the *Monthly Weather Review* was published (by the Signal Service, U.S. Army) in June 1872; the earliest issue of the U.S. Weather Bureau publication *Climatological Data—National Summary* appeared in January 1950 (vol. 1, No. 1). Information concerning individual coastal storms was first tabulated in a section designated "Severe Storms" in the latter publication from January 1950 until December 1953. This section was retitled "Storm Data and Unusual Phenomena" from January 1954 to December 1958. Thereafter, and to the present, similar information has appeared in a separate publication titled *Storm Data,* whose first edition (vol. 1, No. 1) was issued in January 1959.

The first daily surface synoptic weather map of the United States, including adjoining waters of the Atlantic and Pacific oceans (but of course lacking synoptic weather data from ships at sea until the advent of marine radio) was published as a War Department Weather Map by the Signal Service, U.S. Army, on January 1, 1871. The first representation of weather fronts on these maps was not begun until August 1, 1941. Other data are given in the explanatory comments preceding the appropriate groups of weather maps included in part II, chapter 7.

Data on storm surges are also available in many sources, including those listed in the bibliography at the end of this volume. However, it is important to note in connection with the list of tidal flooding events contained in tables 1, 2 that the existence of a storm surge does not necessarily imply tidal flooding unless the amplitude of the surge exceeds the land-flooding level at the point under consideration. A storm surge is defined as an additional increment to the observed tide as meteorological factors cause the water level to rise above that of the predicted astronomical tide. The specific meteorological contributions in this case are a strong, sustained, onshore wind and/or decreasing atmospheric pressure.

A surge therefore represents the positive residual in the total height of the observed tide in excess of the height appearing in tide tables for that date and time.[f] In order for coastal flooding to occur, the combined water level from these two causes must be higher than the level of the adjoining land. The height of the storm surge above mean sea level must be considered in terms of the elevation of the shoreline with respect to this same datum plane in order to establish the possibility for coastal flooding. By the same token, the use of observed (recorded) hourly height data for the tides is not meaningful until referenced to the actual flood level for the point in question. All such cases of shoreline inundation cited in tables 1, 2 are confirmed by published eyewitness accounts.

Table 1

List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976

Explanatory Comments

Table 1 consists of a compilation of 100 cases of severe coastal flooding caused by the combined action of perigean spring tides and near-coincident, strong, persistent, onshore winds. As indicated by the reference sources given in the table, almost all of these instances of tidal flooding are of a magnitude to warrant mention in contemporary local or regional newspapers and/or to be cited as of considerable consequence among historical accounts, monthly and annual meteorological reviews, coastal storm summaries, or other technical sources of marine data. The documented examples of tidal flooding listed are, therefore, semantically distinct from the more restricted category of *meteorological storm surges*. As described in the foregoing section on meteorological data sources and nomenclature, storm surges may or may not be accompanied by coastal flooding.

The arrangement of items in table 1 which, as a master listing, will be referred to repeatedly throughout this volume is:

(1) the key number of the flooding event, as explained in complete detail on page 13 (col. 1), and in the Explanatory Comments preceding table 5;

(2) the date(s) of tidal flooding at the locations in question. Both Old Style and New Style Calendar dates are given where applicable, according to the procedure for reckoning these dates specified in the aforementioned portion of the main text;

(3) the cities, towns, seaports, coastal or beach locations at which tidal flooding is documented by the reference sources as having occurred;

(4) the date and time (to the nearest hour) of the lunar perigee occurring closest in time to (either preceding or following) the instance of tidal flooding. For convenience in reference, the times given are uniformly converted from the Greenwich civil time or ephemeris time of astronomical tables to 75°W.-meridian time (since 1884, designated as eastern standard time). If a location on the west coast of North America is given in col. (3), an additional 3 hours must be subtracted from those given in cols. (4), (5), and (8) to obtain 120°W.-meridian time (Pacific standard time);

(5) the date and eastern standard time (specified to the nearest minute) of the syzygy alignment (either new moon or full moon) closest to the occurrence of the tidal flooding;

(6) the algebraic difference in time between the occurrences of perigee and syzygy nearest to the flooding event, taken in the sense perigee minus syzygy, and rounded off to the nearest hour;

(7) the particular phase of syzygy represented—either new moon (NM) or full moon (FM);

(8) the mean epoch of perigee-syzygy, obtained by adding one-half the difference in hours given in col. (6) (without regard to algebraic sign) to the time of the earliest of these two phenomena; and

(9) documentary sources of the flooding event, given variously as a citation to a contemporary newspaper (with newspaper title coded, plus date, page, and columns) or a professional journal, book, or other reference in which a more detailed description of the flooding event occurs. The coding numbers used for each reference source are listed at the end of table 4d.

With the single exception of Case No. 70 ($P-S= -87^h$), all accompanying perigee-syzygy alignments have a separation-interval between the two components not exceeding $\pm 84^h$ (± 3.5 days). This is the arbitrary limit of separation established in this study in order to include pseudo-perigean spring tides as well as perigean spring and proxigean spring tides. Among the data of table 1, a comparative summary is available indicative of (1) the possible divergences of the times of flooding from the mean epochs of perigee-syzygy within which the special tide-raising influences of this dual alignment are felt, and (2) the greatest separation-interval between perigee and syzygy at which the combined gravitational action has a distinct effect.

[f] Conversely, a *negative* storm surge refers to the depression of local water levels below those predicted from the existing astronomical forces; it is caused by a strong, persistent, *offshore* wind and/or rapidly increasing atmospheric pressure.

Table 1.—*List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976, Related to the Near-Contiguous* Occurrence of Perigean Spring Tides Coupled With Strong, Persistent, Onshore Winds*

(All times given correspond to the meridian of 75°W. longitude)

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Notes and Reference Sources for Flooding (See key at end of table 4d.)
1	1683/84 Mar. 22 (O.S.). 1684 Apr. 1 (N.S.).	Boston, Cambridge, Charlestown (Mass.).	1684 Mar. 31 0100	Mar. 30 2100	+4	FM	1684 Mar. 30 2300	(18) p. 25.
2	1693 Oct. 19 (O.S.). 1693 Oct. 29 (N.S.).	From Virginia settlements on the Delmarva peninsula to Long Island (N.Y.).	1693 Oct. 29 0600	Oct. 28 2300	+7	NM	1693 Oct. 29 0230	(15) p. 17.†
3	1704/05 Jan. 15 (O.S.). 1705 Jan. 26 (N.S.).	Boston, Salem (Mass.); Newport (R.I.).	1705 Jan. 25 1400	Jan. 25 0000	+14	NM	1705 Jan. 25 0700	(18) p. 41.
4	1722/23 Feb. 24 (O.S.). 1723 Mar. 7 (N.S.).	Boston, Dorchester, Chatham, Plymouth, Marblehead, Cape Cod, Salem, Mass.; Hampton, N.H.; Falmouth, Me.	1723 Mar. 6 1300	Mar. 6 1900	−6	NM	1723 Mar. 6 1600	(4) p. 16; (6) pp. 41–42; (48) 2/21–28/1723 (O.S.), p. 2, col. 2; (75) p. 269, fn. 1.
5	1770 Jan. 8	New England, especially near Boston, Mass.	1770 Jan. 10 1500	Jan. 11 1200	−21	FM	1770 Jan. 10 0130	(6) pp. 78–82.
6	1775 Sept. 9	Halifax, Nova Scotia, and Newfoundland, Sept. 9–11.	1775 Sept. 8 0700	Sept. 9 1000	−27	FM	1775 Sept. 8 2030	(5) 12/1775, p. 581; (15) p. 27†; (20) v. 2, p. 1261.
7	1786 Dec. 4–5	Boston, Nantucket, Mass.; and New England.	1786 Dec. 4 1500	Dec. 5 0800	−17	FM	1786 Dec. 4 2330	(6) p. 124; (10) pp. 81–86; (18 pp. 70–71; (45) 12/11/1786 (N.S.), No. 1690, p. 3, col. 1.
8	1802 Mar. 1–2	Coast of Massachusetts	1802 Mar. 2 2300	Mar. 4 0000	−25	NM	1802 Mar. 3 1130	(6) pp. 161–167; (18 p. 166, col. 2.
9	1830 Mar. 26	Portland, Me.; Portsmouth, N.H.; Newburyport, Gloucester, Beverly, Salem, Danversport, Lynn, Boston, Charlestown, and Cambridge, Mass.	1830 Mar. 24 2000	Mar. 24 1000	+10	NM	1830 Mar. 24 1500	(6) pp. 249–251; (49) 3/30/1830, p. 2, col. 2.
10	1839 Dec. 15	Boston, Newburyport, Plum Island, Salem, Marblehead, Cohasset, Plymouth, and Cape Cod, Mass.	1839 Dec. 18 1400	Dec. 20 2100	−55	FM	1839 Dec. 19 1730	(6) pp. 266–272; (19) p. 34, col. 2, p. 35, col. 1.
[11 *6.5*	1846 Mar. 1	Bodie's Island and Hatteras Banks, N.C.	1846 Feb. 24 0900	Feb 25 1432	−30	NM	1846 Feb. 25 0000	(23) pp. 37, 77.
12]	1846 Sept. 7–8	Bodie's Island, Hatteras Banks, N.C.; coastline along Pamplico (Pamlico) Sound; Oregon Inlet.	1846 Sept. 4 1700	Sept. 5 0800	−15	FM	1846 Sept. 5 0030	(12) pp. 138, 282. Possible hurricane; but see tidal backwash attribution for flooding and breaching of spit associated with *offshore* northwesterly wind in (15) p. 131; see also table 2, and text, part I, ch. 2; (23) pp. 37, 77.

13	1851 Apr. 14–16	Minot's Lighthouse, Cohasset, Scituate Harbor, Dorchester, Deer Island, Shirley Gut, Winthrop, Pleasant Beach, Salem, Gloucester, and Boston, Mass.; Newcastle, N.H.	1851 Apr. 13 1300	Apr. 15 1800	−53	FM	1851 Apr. 14 1530	(6) pp. 302–310; (10) pp. 128–138.
14	1861 Nov. 2	New Jersey coast, between Jersey City and Newark, N.J., and northward to Boston, Mass.	1861 Nov. 2 1200	Nov. 2 1100	+1	NM	1861 Nov. 2 1130	(51) 11/4/1861, p. 1, cols. 5, 6.
15	1869 Oct. 5	Cobequid Bay, Burncoat Head, and Noel Bay, Nova Scotia; also northern Maine in vicinity of Eastport. (Perigean spring tides amplified by "Saxby's Gale.")	1869 Oct. 5 0200	Oct. 5 0900	−7	NM	1869 Oct. 5 0530	(8) pp. 11, 16; (13) pp. 253–259. Probably a greatly modified hurricane; see (15) p. 109, and text, part I, ch. 4; (15) pp. 108–11.
16	1870 Oct. 25	Cumberland Basin, New Brunswick	1870 Oct. 25 0000	Oct. 24 1100	+13	NM	1870 Oct. 24 1730	(8) pp. 15, 28, 30, 31.
17	1873 Aug. 9	Pictou, Nova Scotia	1873 Aug. 9 0600	Aug. 8 0900	+21	FM	1873 Aug. 8 1930	(7) 1902, p. 12.
18	1877 Nov. 1–2	North Atlantic coast	1877 Nov. 1 2042	Nov. 5 0348	−79	NM	1877 Nov. 3 1230	(51) 11/3/1877, p. 3, col. 2.
19	1878 Oct. 23	New York City and Coney Island, N.Y.; Brighton Beach, Long Branch, and Sandy Hook, N.J.; Chester, Greenpoint, and Philadelphia, Pa.	1878 Oct. 25 0100	Oct. 25 1800	−17	NM	1878 Oct. 25 0930	(51) 10/24/1878, p. 1, col. 7; (57) 10/24/1878, p. 1, cols. 2, 3; (64) 10/24/1878, p. 1, col. 3.
20	1882 Sept. 28	Long Branch, Highland Beach, Sea Bright, Atlantic Highlands, and Asbury Park, N.J.	1882 Sept. 26 1400	Sept. 27 0000	−10	FM	1882 Sept. 26 1900	(51) 9/29/1882, p. 5, col. 2.
21	1885 Nov. 24	Boston, Revere, and Winthrop, Mass.; Long Island, Rockaway Beach, Yonkers, and Peekskill, N.Y.; Asbury Park, Atlantic City, and Rahway, N.J.	1885 Nov. 25 0330	Nov. 22 1630	+59	FM	1885 Nov. 23 2200	(46) 11/25/1885, p. 1, cols. 4–6.
22	1887 Oct. 12	Moncton, New Brunswick	1887 Oct. 16 1300	Oct. 16 1800	−5	NM	1887 Oct. 16 1530	(7) 1899, p. 5.
23	1891 Oct. 13	Atlantic City, Long Branch, Asbury Park, Sea Bright, Cape May, and Sandy Hook, N.J.	1891 Oct. 16 1300	Oct. 17 0900	−20	FM	1891 Oct. 16 2300	(51) 10/14/1891, p. 1, col. 5.
24	1894 Jan. 22	Cape Hatteras, N.C.	1894 Jan. 20 1000	Jan. 21 1000	−24	FM	1894 Jan. 20 2200	(11) pp. 147–148; (54) 1/26/1894, p. 2, cols. 3–4.
25	1895 Feb. 8–9	Bangor, Me.; Portsmouth, N.H.; Providence and Newport, R.I.; Gloucester, New Bedford, Cape Cod, and Boston, Mass.; Sandy Hook, N.J.; Staten Island, N.Y.; Halifax, Nova Scotia.	1895 Feb. 9 0800	Feb. 9 1200	−4	FM	1895 Feb. 9 1000	(47) 2/9/1895, p. 3, col. 6; 2/11/1895, p. 3, col. 4; (51) 2/9/1895, p. 3, col. 4; 2/10/1895, p. 1, cols. 3–7 and p. 2, col. 1.
[26 *1*	1896 Oct. 8	Between Amherst, Nova Scotia, and Sackville, New Brunswick.	1896 Oct. 7 0000	Oct. 6 1700	+7	NM	1896 Oct. 6 2030	(7) 1899, p. 31, 1901, p. 22.
27]	1896 Nov. 6	Pictou, Nova Scotia, and Charlottetown, Prince Edward Island.	1896 Nov. 4 1200	Nov. 5 0300	−15	NM	1896 Nov. 4 1930	(7) 1902, pp. 12–13.

See footnotes at end of table.

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TABLE 1.—*List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976, Related to the Near-Contiguous* Occurrence of Perigean Spring Tides Coupled With Strong, Persistent, Onshore Winds*—Continued

(All times given correspond to the meridian of 75°W. longitude)

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Notes and Reference Sources for Flooding (See key at end of table 4d.)
28	1897 Nov. 27	Pictou, Nova Scotia	1897 Nov. 24 1000	Nov. 24 0400	+6	NM	1897 Nov. 24 0700	(7) 1902, p. 12.
29	1899 Feb. 9	New York, N.Y.	1899 Feb. 9 0900	Feb. 9 0400	−19	NM	1899 Feb. 9 1830	(25b) v. 27, no. 2 (2/1899), pp. 41–44; (51) 2/9/1899, p. 4, col. 3.
6.5								
30	1899 Aug. 17	Newport News, Va., and Va. coast	1899 Aug. 20 1700	Aug. 21 0000	−7	FM	1899 Aug. 20 2030	(59) 8/18/1899, p. 1, col. 7.
31	1900 Oct. 11–12	Charlottetown and Summerside, Prince Edward Island.	1900 Oct. 8 0100	Oct. 8 0800	−7	FM	1900 Oct. 8 0430	(7) 1902, pp. 15–16.
32	1901 Apr. 20	Between Amherst, Nova Scotia, and Sackville, New Brunswick.	1901 Apr. 18 1600	Apr. 18 1700	−37 *min.*	NM	1901 Apr. 18 1630	(7) 1901, p. 22.
1								
33	1901 May 18	Between Amherst, Nova Scotia, and Sackville, New Brunswick.	1901 May 17 0200	May 18 0100	−23	NM	1901 May 17 1330	(7) 1901, p. 22.
6.5								
34	1901 Nov. 24	Asbury Park, Jersey City, Sandy Hook, Sea Bright, and Shrewsbury, N.J.; Manhattan and Coney Island, N.Y.; New Haven, Stamford, and Greenwich, Conn.; Chatham and Provincetown, Mass.	1901 Nov. 25 1100	Nov. 25 2000	−9	FM	1901 Nov. 25 1530	(51) 11/25/01, p. 1, col. 7; p. 2, cols. 3, 4.
35	1908 Feb. 3	Port aux Basques, Newfoundland; Harrington Harbour, Quebec.	1908 Feb. 1 2000	Feb. 2 0400	−8	NM	1908 Feb. 2 0000	(35) 2/3/08, p. 4, col. 2.
36	1909 Dec. 26	Boston, Mass.	1909 Dec. 23 0348	Dec. 26 1630	−84	FM	1909 Dec. 24 2200	(11) pp. 257–258; (25b) v. 38, No. 1 (1/10), p. 4; (46) 12/27/09, p. 1, cols. 1–4; p. 2, cols. 2–8, p. 5, cols. 5–8; (75) p. 269 and fn. 1, p. 270, fn. 4.
37	1914 Nov. 20	Quebec, Quebec	1914 Nov. 16 2300	Nov. 17 1100	−12	NM	1914 Nov. 17 0500	(9) p. 14.
1								
38	1914 Dec. 17–18	Long Beach, Balboa, and Los Angeles, Calif.	1914 Dec. 15 0912	Dec. 16 2135	−36	NM	1914 Dec. 16 0300	(30) 12/18/14, pt. II, p. 1, cols. 4–5, p. 6, cols. 3–5.
39	1915 Apr. 3	Virginia Beach and Cape Henry, Va.; Cape Hatteras, N.C.	1915 Apr. 1, 1848	Mar. 31 0038	+42	FM	1915 Mar. 31 2200	(11) p. 191; (61) 4/4/15, p. 1, col. 1, p. 2, col. 7, p. 4, cols. 2–3, and p. 5, col. 3.
40	1916 July 13	Charleston, S.C.	1916 July 14, 1900	July 15 0000	−5	FM	1916 July 14 2130	(51) 7/14/16, p. 20, col. 4.
41	1917 Oct. 1	Moncton and Sackville, New Brunswick; Amherst and Windsor, Nova Scotia.	1917 Sept. 29, 1306	Sept. 30 1531	−27	FM	1917 Sept. 30 0230	(9) p. 95.
1								

42	1917 Oct. 31......	Moncton, New Brunswick, and, to a lesser degree, at Sackville, New Brunswick, and Amherst, Nova Scotia.	1917 Oct. 27, 1748	Oct. 30 0119	−55	FM	1917 Oct. 28 2130	(9) p. 95.
A–43 *7.5*	1918 Apr. 10–12...	Sea Bright, Atlantic City, N.J.; Staten Island, Rockaway Beach, and southern Long Island, N.Y.	1918 Apr. 10, 0500	Apr. 11 0000	−19	NM	1918 Apr. 10 1430	(51) 4/11/18, p. 15, cols. 5, 6; 4/13/18, p. 11, col. 3; 4/13/18, p. 11, col. 3.
44	1918 Nov. 18......	New York, N.Y.; Batiscan, Quebec...	1918 Nov. 16, 2230	Nov. 18 0233	−29	FM	1918 Nov. 17 1230	(51) 11/19/18, p. 9, col. 3, p. 22, col. 3; 11/25/18, p. 12, col. 6.
45	1919 Nov. 7.......	Manhattan and Coney Island, N.Y...	1919 Nov. 8, 0900	Nov. 7 1900	+14	FM	1919 Nov. 8 0200	(51) 11/8/19, p. 5, col. 1; 11/9/19, p. 10, col. 6.
46	1922 Jan. 11......	Sea Bright, Clifton, and Long Branch, N.J.	1922 Jan. 14, 1848	Jan. 13 0936	+33	FM	1922 Jan. 14 0230	(51) 1/12/22, p. 6, cols. 4–5.
47	1923 Dec. 8.......	South Bend and Raymond, Wash....	1923 Dec. 6 2200	Dec. 7 2100	−23	FM	1923 Dec. 7 0930	(63) 12/9/23, p. 16, HH, col. 3.
48	1926 Feb. 11–13...	Los Angeles, Long Beach, San Diego, Capistrano Beach, and Ventura, Calif.	1926 Feb. 12 0700	Feb. 12 1200	−5	NM	1926 Feb. 12 0930	(33) 2/14/26, p. 1, col. 4; (34) 2/14/26, p. 1, cols. 6–7; (51) 2/14/26, p. 7, cols. 2–3.
49	1926 June 28......	Cape Hatteras, N.C...............	1926 June 28 0448	June 25 1613	+61	FM	1926 June 26 2300	(12) p. 246.
B–50 *1*	1927 Mar. 3–4.....	New England coast...............	1927 Mar. 4 0500	Mar. 3 1400	+15	NM	1927 Mar. 3 2130	(44) 3/3/27, p. 1, col. 3; (51) 3/4/27, p. 23, col. 1.
C–51	1927 Apr. 2.......	Atlantic City, N.J.; and Delaware...	1927 Apr. 1 1700	Apr. 1 2300	−6	NM	1927 Apr. 1 2000	(51) 4/3/27, sec. 1, p. 19, col. 2; (39) 4/5/27, p. 3, col. 4.
52	1927 Dec. 5.......	Atlantic City, N.J................	1927 Dec. 6 2000	Dec. 8 1232	−41	FM	1927 Dec. 7 1630	(51) 12/5/27, p. 13, col. 2.
53 *7.5*	1929 Apr. 11–12...	Coastal regions of New York and New Jersey.	1929 Apr. 12 1630	Apr. 9 1533	+73	NM	1929 Apr. 11 0400	(51) 4/11/29, p. 60, col. 8; 4/12/29, p. 5, col. 2; 4/13/29, p. 35, col. 5; 4/14/29, p. 1. col. 5, p. 19, cols. 3–8
54	1929 Nov. 18......	Boston and Winthrop, Mass.........	1929 Nov. 19 0048	Nov. 16 1914	+54	FM	1929 Nov. 17 2200	(51) 11/19/29, p. 20, col. 3.
55	1930 Aug. 23......	From Block Island, N.Y., to Maine...	1930 Aug. 23 1500	Aug. 23 2300	−8	NM	1930 Aug. 23 1900	(51) 8/24/30, p. 1, col. 6, p. 16, col. 1.
56e	1931 Jan. 6........	Boston, Cape Cod, and Peaked Hill, Mass.; Hampton, N.H.	1931 Jan. 6 0948	Jan. 4 0815	+50	FM	1931 Jan. 5 0900	(51) 1/7/31, p. 2, cols. 4–5, p. BQ27, col. 8 (Last Edition); 1/10/31, p. 17, col. 5.
56w *2*	1931 Jan. 6.......	Quinault Indian Reservation, Taholah, Wash.	1931 Jan. 6 0948	Jan. 4 0815	+50	FM	1931 Jan. 5 0900	(51) 1/7/31, p. BQ27, col. 8 (Last Edition).
D–57 *1*	1931 Mar. 4–5.....	Halifax, N.S.; Boston, Salem, Winthrop, Revere, Gloucester, and Newburyport, Mass.; Portsmouth, N.H.; Portland, Me.; New Haven and Greenwich, Conn.; Atlantic City, Jersey City, and Ventnor, N.J.; Rockaway and East Hampton, N.Y.	1931 Mar. 4 0500	Mar. 4 0600	+6 *min.*	FM	1931 Mar. 4 0530	(25b) v. 59, no. 3 (3/31), p. 127; (37) 3/5/31, sec. 1, p. 2, cols. 7, 8; 3/6/31, p. 20, col. 2; (51) 3/6/31, p. BQ48, col. 2; 3/9/31, p. 1, col. 1, 3/10/31, p. 18, cols. 1, 4; (75) p. 270, fn. 4.

See footnotes at end of table.

TABLE 1.—*List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976, Related to the Near-Contiguous* Occurrence of Perigean Spring Tides Coupled With Strong, Persistent, Onshore Winds*—Continued

(All times given correspond to the meridian of 75°W. longitude)

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Notes and Reference Sources for Flooding (See key at end of table 4d.)
E–58	1931 Apr. 1	Boston, Mass.; Flushing, N.Y.; Southampton, Jersey City, Atlantic City, and Long Branch, N.J.	1931 Apr. 1 1700	Apr. 2 1500	−22	FM	1931 Apr. 2 0400	(39) 4/1/31, p. 1, col. 4; (51) 4/2/31, p. 2, cols. 2, 3.
7.5								
59	1932 Nov. 2	New York, N.Y., and coast of New Jersey.	1932 Oct. 29 2200	Oct. 29 1000	+12	NM	1932 Oct. 29 1600	(51) 11/2/32, p. 1, col. 3, p. 3, col. 5.
1								
60	1932 Nov. 30	Boston, Winthrop, Cape Cod, and Nahant, Mass.; Hampton Beach, N.H.	1932 Nov. 27 1000	Nov. 27 2000	−10	NM	1932 Nov. 27 1500	(37) 12/1/32, p. 7, cols. 7, 8.
61	1933 Jan. 27–28	Atlantic City, N.J., to Bar Harbor, Me.	1933 Jan. 22 2148	Jan. 25 1820	−69	NM	1933 Jan. 24 0800	(43) 2/1/33, p. 1, col. 5, p. 6, cols. 3, 6; (51) 1/26/33, p. 1, cols. 2–3; 1/27/33, p. 21, cols. 1, 2; 1/29/33, p. 6, cols. 1–3.
62	1933 Apr. 12	Long Island, N.Y.	1933 Apr. 12 0612	Apr. 10 0838	+46	FM	1933 Apr. 11 0800	(51) 4/13/33, p. 3, col. 2.
63	1933 Dec. 17	Aberdeen, Hoquiam, Cosmopolis, and Montesano, Wash.	1933 Dec. 17 0700	Dec. 16 2200	+9	NM	1933 Dec. 17 0230	(55) 12/18/33, p. 1, col. 2.
64	1934 Aug. 20–22	Newport Beach, Malibu Beach, Laguna Beach, and Balboa, Calif.	1934 Aug. 23 1500	Aug. 24 1500	−24	FM	1934 Aug. 24 0300	(27) Apr. 1935, p. 61, col. 1, par. 2; Oct. 1940, p. 113, col. 1, par. 2; (33) 8/22/34, p. 1, col. 4.
65	1934 Dec. 8	Laguna Beach, Newport Beach, and Santa Monica, Calif.	1934 Dec. 8 0300	Dec. 6 1225	+39	NM	1934 Dec. 7 0800	(27) Apr. 1935, p. 62, col. 1, par. 1; Oct. 1940, p. 113, col. 1, par. 2; (30) 12/8/34, p. 6, col. 4.
7.5								
66	1935 July 16	Oak Beach, Long Island, N.Y.	1935 July 17 2142	July 16 0000	+46	FM	1935 July 16 2300	(51) 7/17/35, p. 14L+, col. 7.
67	1937 Oct. 21–23	Boston, Mass., and New York, N.Y.	1937 Oct. 21 1100	Oct. 19 1648	+42	FM	1937 Oct. 20 1400	(46) 10/21/37, p. 1, col. 8; (51) 10/24/37, sec. 2, p. 1, col. 1.
F–68	1939 Jan. 3–5	Aberdeen, Hoquiam, and Neskowin, Wash.; Marshfield, Astoria, Coos Bay, Seaside, Tillamook, Portland, and Delake, Oreg.; Long Beach and Hermosa Beach, Calif.	1939 Jan. 6 0600	Jan. 5 1600	+14	FM	1939 Jan. 5 2300	(25b) v. 67, No. 1 (1/39), p. 30; (55) 1/4/39, p. 2, cols. 3–6; 1/5/39, p. 1, cols. 4, 7; 1/6/39, p. 1, cols. 4, 7, p. 6, col. 1; 1/7/39, p. 3, cols. 1–5.
G–69	1940 Apr. 21	Boston (Deer Island), Cohasset (Minot's Light and Bassing's Island), Hull, Winthrop, Beachmont, and Quincy, Mass.	1940 Apr. 20 1400	Apr. 21 2337	−34	FM	1940 Apr. 21 0700	(51) 4/22/40, p. 1, col. 2 (Late City Ed.); p. 34L, col. 1.

70	1940 Dec. 25–28...	South Bend and Raymond, Wash.; Delake and Nelscott, Oreg.; Los Angeles, San Pedro, Redondo Beach, and Point Fermin, Calif.	1940 Dec. 25 0100	Dec. 28 1556	−87	NM	1940 Dec. 26 2030	(55) 12/26/40, p. 1, col. 7 (Final Ed.); 12/27/40, p. 1, cols. 1–4 (Final Ed.); (56) 12/27/40, sec. 1, p. 1, col. 3; sec. 3, p. 1, col. 8; 12/28/40, p. 3, cols. 1–5; p. 7, cols. 3–5; 12/29/40, p. 6, col. 2.
71	1944 Nov. 30–Dec. 1.	New Bedford, Cape Cod, Chatham, and Provincetown, Mass.; Long Island, N.Y.; Jersey City and Sea Bright, N.J.; Mt. Desert Island, Me.	1944 Nov. 26 2300	Nov. 29 1952	−69	FM	1944 Nov. 28 0930	(43) 12/7/44, p. 1, col. 1, p. 8, col. 2; (51) 12/1/44, p. 25L, col. 1; 12/2/44, p. 15, col. 1.
H–72	1945 Nov. 20......	Portland, Eastport, and Machiasport, Me.	1945 Nov. 18 2100	Nov. 19 1000	−13	FM	1945 Nov. 19 0330	(40) 11/21/45, p. 1, col. 8.
⌈73	1948 Jan. 2.......	Boston, Mass......................	1947 Dec. 28 1800	Dec. 27 1527	+27	FM	1947 Dec. 28 0430	(51) 1/3/48, p. 3, cols. 2–5 (illustration), 6.
1								
⌊74	1948 Jan. 25–26...	Vicinity of San Francisco, Calif......	1948 Jan. 26 0600	Jan. 26 0200	+4	FM	1948 Jan. 26 0400	(30) 1/26/48, p. 8, col. 6; (33) 1/26/48 p. 1, col. 7.
75	1949 Oct. 18......	Long Branch and Sea Bright, N.J....	1949 Oct. 21 1000	Oct. 21 1600	−6	NM	1949 Oct. 21 1300	(51) 10/19/49, p. 59, col. 1.
76	1951 July 17–18...	Long Beach, Calif.................	1951 July 17 1800	July 18 1400	−20	FM	1951 July 18 0400	(30) 7/19/51, p. 1, col. 1 (Final Ed.).
⌈77	1951 Dec. 3–4.....	San Francisco and Burlingame, Calif.; Duwamish River, Wash.	1951 Nov. 30 0800	Nov. 28 2000	+36	NM	1951 Nov. 29 1400	(62) 12/3/51, p. 16, col. 6; p. 13, col. 2; 12/4/51, p. 1, cols. 3–6.
1								
⌊78	1951 Dec. 29......	San Francisco and San Rafael, Calif..	1951 Dec. 28 1800	Dec. 28 0700	+11	NM	1951 Dec. 28 1230	(33) 12/31/51, p. 1, col. 4; (34) 12/29/51, p. 1, cols. 7, 8 (Final Ed.).
79	1953 Oct. 22–24...	Manhattan, Brooklyn, and New Rochelle, N.Y.; Wildwood and Hamilton Beach, N.J.; Stamford, Conn.; Boston, Mass.	1953 Oct. 21 1100	Oct. 22 0800	−21	FM	1953 Oct. 21 2130	(51) 10/23/53, p. 1, cols. 1, 2; p. 47, cols. 2, 3; 10/24/53, p. 9, cols. 5, 6.
⌈80	1958 Jan. 7–8.....	Along Hampton Roads and the eastern piedmont and tidewater portions of Va.; southern R.I., Cape Cod, and coastal Mass. and N.H.; Wells Beach, Me.	1958 Jan. 8 1900	Jan. 5 1509	+76	FM	1958 Jan. 7 0500	(25a) v. 9, No. 1, p. 9.
1								
⌊81	1958 Feb. 3–4.....	S. San Diego Bay, Imperial Beach, Santa Paula, Long Beach, Alamitos Bay Peninsula, Santa Monica, and Seabright, Calif.	1958 Feb. 5 1800	Feb. 4 0305	+39	FM	1958 Feb. 4 2230	(30) 2/4/58, pt. 1, p. 1, col. 3; 2/5/58, pt. 1, p. 1, cols. 4–5.
2								
82	1958 Apr. 1–2.....	Boston, Nantucket, Winthrop, Chatham, Lynn, and Revere, Mass.; Portsmouth, N.H.	1958 Apr. 3 1500	Apr. 3 2300	−8	FM	1958 Apr. 3 1900	(46) 4/2/58, p. 1, cols. 6–8 (Late City Ed.); 4/3/58, p. 1, col. 3 (Late City Ed.).
I–83e	1959 Dec. 29......	Atlantic City, N.J.; Long Island, N.Y.; Cape Cod, Gloucester, Rockland, and Biddeford, Mass.; Kennebunkport, Me.; Rye, N.H.	1959 Dec. 28 2000	Dec. 29 1400	−18	NM	1959 Dec. 29 0500	(25a) v. 10, No. 12, pp. 465, 466; (25b) v. 87, No. 12 (12/59), p. 457; (25c) v. 1, No. 12, p. 121; (46) 12/30/59, p. 3, cols. 6–8; (51) 12/30/59, p. 6, cols. 3–4.
I–83w	1959 Dec. 30......	San Francisco Bay area, Calif.......	1959 Dec. 28 2000	Dec. 29 1400	−18	NM	1959 Dec. 29 0500	(25c) v. 1, No. 12, p. 120; (32) 12/30/59, p. 1, col. 8.

See footnotes at end of table.

TABLE 1.—*List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976, Related to the Near-Contiguous* Occurrence of Perigean Spring Tides Coupled With Strong, Persistent, Onshore Winds*—Continued

(All times given correspond to the meridian of 75°W. longitude)

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Notes and Reference Sources for Flooding (See key at end of table 4d.)
84e	1961 Jan. 15......	Atlantic City and Ocean City, N.J.; also Delaware. (Strong surface winds, together with intensified subsurface currents associated with perigean spring tides, weakened and destroyed a Texas tower approximately 80 nautical miles offshore, S.E. of New York City, in an area of about 180 ft water depth, on this date as well.)	1961 Jan. 16 1800	Jan. 16 1700	+1	NM	1961 Jan. 16 1730	(38) 1/16/61, p. 1, col. 1; (50) 1/16/61, p. 1, col. 8.
84w	1961 Jan. 15......	San Buenaventura State Park, Ventura County, Calif.	1961 Jan. 16 1800	Jan. 16 1700	+1	NM	1961 Jan. 16 1730	(22) p. 15.
J-85	1962 Mar. 6–7.....	Along entire Atlantic coast from south of Portland, Me., to South Carolina.	1962 Mar. 6 0400	Mar. 6 0500	−31 *min.*	NM	1962 Mar. 6 0430	(24) v. 6, No. 3, pp. 79–85; (25a) v. 13, No. 3, pp. 137–139; (25c) v. 4, No. 3, pp. 134–139; (26) v. 15, No. 3, June 1962, pp. 117–120; (27) Oct. 1962, pp. 4–9; (28) Dec. 1962, pp. 860–887; (51) 3/6/62, p. 24, cols. 2–5; 3/7/62, p. 1, cols. 2, 3 (Late City Ed.); p. 24, cols. 2–4, 3/8/62, p. 1, cols. 6–7; p. 22, cols. 3–8; p. 62, cols. 2–5; 3/9/62, p. 17, cols. 3–6; p. 18, cols. 2–4; (71); (72); (73) ch. 41, pp. 617–659.
7.5								
86	1962 Oct. 13......	Local estuaries and bay locations of Wash. (e.g., Union); Oreg. (e.g., Coos Bay); northern Calif. (e.g., Humboldt Bay); and central Calif. (e.g., Pacifica and Redwood City drainage areas)	1962 Oct. 12 2300	Oct. 13 0800	−9	FM	1962 Oct. 13 0330	(14) pp. 9, 20, 43, 147; (31) 10/18/62, pp. 1–3, 6–8.
1								
K-87	1962 Nov. 10–14...	Cape May to Sandy Hook, N.J.; (coastal erosion from Fire Island to Montauk Point, L.I.); New York City; Bridgeport, Conn.; Cape Cod and Nantucket Island, Mass.; coastal lowlands, Maine	1962 Nov. 10 0900	Nov. 11 1704	−32	FM	1962 Nov. 11 0100	(25c) v. 4, No. 11, pp. 118–119; (51) 11/11/62, sec. 1, p. 44, col. 1; 11/15/62, p. 39, col. 8.

88	1965 Sept. 26	Capistrano Beach, Calif.	1965 Sept. 22 1800	Sept. 24 2218	−52	NM	1965 Sept. 23 2000	(32) 9/27/65, p. A–20, col. 5.
89	1967 Apr. 27	Atlantic City, N.J.	1967 Apr. 23 1400	Apr. 24 0700	−17	FM	1967 Apr. 23 2230	(51) 4/28/67, p. 46–L, cols. 2–4; 4/30/67, p. 85–L, col. 4.
7.5								
90	1967 Nov. 28–Dec. 3.	Coasts of Massachusetts and southern New England.	1967 Nov. 30 0900	Dec. 1 1110	−26	NM	1967 Nov. 30 2200	(24) Nov. 1967, p. 208, col. 2, par. 3.
91	1969 Dec. 4–14	Rincon Point, Ventura, Ocean Beach, Oceanside, Carlsbad, and Del Mar, Calif.	1969 Dec. 10 0600	Dec. 9 0443	+25	NM	1969 Dec. 9 1730	(24) Mar. 1970, p. 104, col. 2, par. 4; May 1970, p. 149; cols. 1, 2, par. 1; Sept. 1970, p. 259, cols. 1–2.
92	1970 Mar. 5–6	Capistrano Beach and Newport Beach, Calif.	1970 Mar. 6 0500	Mar. 7 1243	−32	NM	1970 Mar. 6 2100	(30) 3/7/70, p. 1, cols. 1, 2; p. 10, cols. 1, 2.
L–93e	1971 Mar. 26	Virginia Beach, Norfolk, and Portsmouth, Va.	1971 Mar. 26 0400	Mar. 26 1400	−10	NM	1971 Mar. 26 0900	(24), Sept. 1971, p. 293, col. 1; p. 297, col. 1; (60) 3/27/71, p. 1, cols. 2–4.
L–93w	1971 Mar. 26	Oxnard Shores, near Oxnard, Calif.	1971 Mar. 26 0400	Mar. 26 1400	−10	NM	1971 Mar. 26 0900	(22) p. 17.
1								
94	1971 Apr. 22	Oxnard Shores, Calif.	1971 Apr. 23 1300	Apr. 24 2302	−34	NM	1971 Apr. 24 0600	(22) p. 30; (30) 4/23/71, pt. 1, p. 3, cols. 1, 4; 4/24/71, p. 1, col. 4, 2/26/71, p. 1, col. 1; (32) 4/23/71, p. 1, cols. 4, 5.
95	1971 Dec. 3	Winyah Bay, Georgetown, and Pawleys Island, S.C.	1971 Nov. 30 0600	Dec. 2 0249	−45	FM	1971 Dec. 1 0430	(21) p. 6.
96	1972 Feb. 18–20	Along Hampton Roads, Va., to Stamford, Conn.; Old Orchard Beach, Kennebunkport, and Portland, Me.	1972 Feb. 17 1400	Feb. 14 1929	+67	NM	1972 Feb. 16 0430	(24) May 1972, pp. 201–202; (25b) v. 101, no. 4 (4/73), pp. 363–370; (36) 2/20/72, p. A–1, col. 5; (41) 2/20/72, p. 1, col. 3, p. 28A, cols. 1, 2; (42) 2/19/72 (Weather), col. 7; 2/21/72, p. 1, cols. 6–7, p, 10, cols. 6–7, p. 14, cols. 2–6, p. 20, cols. 4–7.
97	1972 Nov. 20	Rincon to Oxnard, Oxnard Shores, and Hollywood-by-the-Sea, Calif. also, on Nov. 25–26: coastal beaches of Oregon and Washington; Gulf of Alaska.	1972 Nov. 20 1900	Nov. 20 1800	+53 *min.*	FM	1972 Nov. 20 1830	(55) 11/24/72, p. 6, 2M (illustration); 11/28/72, p. 4, J–4M, cols. 6–8.
M–98e	1973 Dec. 11	Halifax, Nova Scotia	1973 Dec. 10 1800	Dec. 9 2100	+21	FM	1973 Dec. 10 0730	Verbal confirmation from marine weather forecaster, Boston office, National Weather Service.
M–98w	1973 Dec. 11	Tokeland, Raymond, and South Bend, Wash.; Seaside, Astoria, and Newport, Oreg.	1973 Dec. 10 1800	Dec. 9 2100	+21	FM	1973 Dec. 10 0730	(56) 12/12/73, p. 24 3M, cols. 4, 5; (63) 12/12/73, p. 1, cols. 1–4; (69) p. 1.
1								
N–99	1974 Jan. 8	Santa Barbara, Santa Monica, and San Clemente; also Newport Beach, Capistrano Beach, and Malibu Beach, Calif.	1974 Jan. 8 0600	Jan. 8 0800	−2	FM	1974 Jan. 8 0700	(30) 12/26/73, p. 1, cols. 2, 3; 1/7/74, sec. 1, p. 3, col. 3; 1/9/74, pt. 1, p. 1, cols. 5–7; p. 29, cols. 1, 2.

See footnotes at end of table.

TABLE 1.—*List of 100 Representative Examples of Major Coastal Flooding Along the North American Coastline, 1683–1976, Related to the Near-Contiguous* Occurrence of Perigean Spring Tides Coupled With Strong, Persistent, Onshore Winds*—Continued

(All times given correspond to the meridian of 75°W. longitude)

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Notes and Reference Sources for Flooding (See key at end of table 4d.)
O–100	1976 Mar. 16–17...	Ogunquit, Cranberry Island, Popham Beach, Saco, and Kennebunkport, Me.; New Castle, Rye, Hampton Beach, and Portsmouth, N.H.; Marblehead, Provincetown, and Plum Island, Mass.; Halifax, Nova Scotia.	1976 Mar. 16 1400	Mar. 15 2200	+16	FM	1976 Mar. 16 0600	(25c) v. 18, No. 3, p. 8; (65) 3/19/76, p. 1, cols. 1–6, (66) 3/17/76, v. 93, No. 133, p. 1, cols. 1–4; (67) 3/17/76, v. 12, No. 11, p. 1, col. 1; (68) 3/17/76, v. XC, No. 143, p. 1, col. 1.

*The distribution frequency for the intervals of time between each of the observed tidal floodings and the corresponding mean epochs of perigee-syzygy is significant in showing a strongly contributing astronomical causal relationship. This distribution in terms of numbers of cases of tidal flooding observed is: For an interval of $<1^d$, 33; $\pm 1^d$, 30; $\pm 2^d$, 18; $\pm 3^d$, 12; $\pm 4^d$, 6; $\pm 5^d$, 1. Fully 81% of the cases of extreme tidal flooding cataloged therefore occur within $\pm 2^d$ of perigee-syzygy, 93% within $\pm 3^d$, and 99% within $\pm 4^d$. This is the basis for the ±3.5-day divergence limit for major perigee-syzygy effectiveness set throughout this volume.

From this consideration, it is also obvious that there really is no such thing as a simple *perigean tide*, since when the Moon is more than the 3.5-day interval from perigee-syzygy (within which *perigean spring* tides exist) it is within approximately 3.5^d of quadrature, and the diminished effects of *perigean neap* tides are felt.

In this evaluation, cases in which flooding occurs on both the east and west coasts (even a day apart, as in Nos. 83e, w) are counted as one event, having the largest of the two divergences from the mean of perigee-syzygy.

Of significance to the analysis of major tidal flooding is the fact that, with only one exception (No. 70) in the preceding table, the separation-interval between perigee and syzygy also is less than, or equal to, $\pm 84^h$ ($\pm 3.5^d$).

For all cases of tidal flooding for which the corresponding perigee-syzygy data are obtained from the computer printout of table 16 (those in which $P-S=\pm 24^h$ and syzygy times are rounded off to the nearest hour only), the calendar day of the week may be established, where desired, from the Julian Day given in this printout. (See the Explanatory Comments preceding table 16.)

†The storm accompanying this perigean spring tide is of uncertain, but possible hurricane origin. That associated with No. 2 is cited in the *Philosophical Transactions, 19*, of the Royal Society of London, August 1697, p. 659, only as the "Great Storm at Acomack" (a part of the presently designated Delmarva Peninsula). A similarly debatable situation exists in the case of No. 6, where the observed storm superimposed upon perigean spring tides was far north of the usual region of intensification of tropical storms and hurricanes. (See the Explanatory Comments on historical hurricanes preceding table 2.)

Accordingly, although a few of the examples given may seem to exceed, by a day or so, the tolerance limit in which the influence of perigean spring tides would normally be expected, a comparison with the circumstances of the astronomical alignment and the predicted daily tidal ranges around this time reveals that: (1) such apparently more divergent examples are still especially close to perigee, although possibly several days removed from syzygy; (2) the predicted tidal level is above that of mean high water springs; or (3) the height predicted is of a magnitude approaching—and therefore over a 19-year cycle of compilation, contributory to—the upper limit of this averaged value of maximum high tides for the station in question. A representative few such more divergent cases are, accordingly, included in the table for completeness. These serve to show the tidal lifespan of perigean spring tides in terms of their permissible divergence from the epoch of maximum perigee-syzygy influence—particularly in the case of those examples of tidal flooding that last over several successive days.

A significant factor of event correlation between the individual entries of this table is indicated in col. (2) by the brackets connecting instances of tidal flooding related within the principal short-range cycles of perigee-syzygy alignment. These relationships may involve the circumstances of successive floodings coincident with: (1) the approximate 28.5-day repetition of perigee-syzygy alignment, once attained (the average between the anomalistic and synodic months); (2) occasional double or triple multiples of this period; or (3) the 6.5- to 7.5-month average interval between perigee-syzygy occurrences discussed in chapter 6. The contributing role to tidal flooding provided by the heightened astronomical tide-raising influences at times of perigee-syzygy is substantially confirmed by this evidence.

Table 2

A Representative List of North American Hurricanes Occurring Nearly Concurrently With Perigean Spring Tides

Explanatory Comments

In the modern precise definition of the word *hurricane,* only two principal criteria are involved: (1) that the surface winds within the intense, low-pressure cyclonic system forming the hurricane shall, at the time of its being so designated, have a sustained velocity equal to 74 miles per hour (64.3 knots) or greater; and (2) that the incipient hurricane shall have an origin over tropical or subtropical waters.

The expression *hurricane* applies to storms possessing the above characteristics and occurring either on the east or west coast of North America, in the Gulf of Mexico, or the Caribbean Sea. In all cases, the hurricane originates over tropical or subtropical waters. On the east coast, the hurricane may penetrate to middle or even high latitude before recurving eastward, moving inland, or, with a loss of thermal energy at high latitudes, dissipating completely. On the west coast, the hurricane only infrequently moves out of subtropical waters to landfall on the California shoreline (usually not traveling farther north than the Gulf of Lower California). However, the term hurricane is used in connection with all such storms occurring in lower latitude portions of the North Pacific Ocean, east of the international dateline.

The word *typhoon* characterizes similar storms found in the China Sea and in the North Pacific Ocean, west of the international dateline. The term *tropical cyclone* properly refers to such storms originating in the Indian Ocean to the south of India, off the southeast coast of Africa, in the Bay of Bengal, or the Arabian Sea. *Baguio* is the expression used for hurricanes in the Philippine Islands. Although the four preceding terms are synonymous, it is important to note that a *tropical depression* has not yet reached the intensity of any of these storms—or, alternatively, after a filling and weakening of the low pressure center, has been downgraded from hurricane strength.

Gordon E. Dunn and Banner I. Miller in their book on *Atlantic Hurricanes* [4] (appendix B) have included the following relative intensity scale for hurricanes, based upon the maximum winds and minimum atmospheric pressure associated with them. Since both these quantities are lacking in connection with early American hurricanes, the intensity ratings in these cases have been inferred or extrapolated from contemporary eye-witness accounts of the apparent strength of the storm, judged from observed wind-damage and tidal flooding effects, including destruction of property and any loss of life involved. The Beaufort scale for estimating relative wind intensities did not become available until 1806.

The Intensity Classification of Hurricanes

Intensity classification	Maximum winds	Minimum central pressure
Minor.......	$<$74 mph ($<$64 kn)	$>$29.40 in. ($>$996 mb)
Minimal.....	74 to 100 mph (64 to 87 kn)	29.03 to 29.40 in. (983 to 996 mb)
Major.......	101 to 135 mph (88 to 117 kn)	28.01 to 29.00 in. (949 to 982 mb)
Extreme.....	$\geq$136 mph ($\geq$118 kn)	$\leq$28.00 in. ($\leq$948 mb)

A list and description of "Hurricanes Affecting the United States, by Sections," 1635–1963, is contained in appendixes B, C of the aforementioned work, and hurricanes, 1493–1951, are described in chapters XII–XV and appendix of Ivan R. Tannehill's book on *Hurricanes* [14]. In addition, such hurricanes are discussed, and documented with both contemporary and later sources, in David M. Ludlum's *Early American Hurricanes, 1492–1870.* [5]

In the present work, the purpose of table 2 and item A–2, "Summary and Conclusions," chapter 8, is to consider the coastal flooding potential added to *hurricanes* by their coincidence or near-coincidence with perigean spring tides. With a few uncertain examples, table 1 likewise contains only cases of coastal flooding generated by the combination of perigean spring tides and *offshore storms.* Because of the previously mentioned, often completely subjective methods of wind velocity appraisal, it is difficult to establish with absolute cer-

TABLE 2.—*A Representative List of North American Hurricanes Occurring Nearly Concurrently With* Perigean Spring Tides*

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Reference Sources for Flooding (See key at end of table 4d.)
200	1635 Aug. 14–16 (O.S.). Aug. 24–26 (N.S.).	Gloucester, Cape Cod, and Boston, Mass., etc.; Buzzard's Bay and Providence, R.I.; Connecticut.	1635 Aug. 29 1600	Aug. 27 2200	+42	FM	1635 Aug. 28 (N.S.) 1900	(1) pp. 279–280; (2) entry of 8/16/1635; (3) pp. 102–103; (6) pp. 3–10; (10) pp. 34–46; (15) pp. 10–13.
202	1638 Aug. 3 (O.S.). Aug. 13 (N.S.).	Rhode Island, Connecticut, and Massachusetts.	1638 Aug. 9 1500	Aug. 9 1300	+2	NM	1638 Aug. 9 (N.S.) 1400	(15) p. 13.
211	1683 Aug. 13 (O.S.). Aug. 23 (N.S.).	New Hampshire and, by blocking hydrological runoff, in Connecticut.	1683 Aug. 22 2300	Aug. 22 0500	+18	NM	1683 Aug. 22 1400	(15) pp. 16–17.
215	1693 Oct. 19 (O.S.). Oct. 29 (N.S.).	Delmarva peninsula, and from Virginia to Long Island, N.Y.	1693 Oct. 29 0600	Oct. 28 2300	+7	NM	1693 Oct. 29 0230	(15) p. 17.
238	1743 Oct. 22 (O.S.). Nov. 2 (N.S.).	Boston, Mass. etc.	1743 Nov. 4 2300	Nov. 2 0300	+68	FM	1743 Nov. 3 1300	(15) pp. 22–23.
253	1803 Oct. 2–3	Norfolk, Va.	1803 Oct. 1 0400	Sept. 30 1900	+9	FM	1803 Sept. 30 2330	(15) p. 192.
254	1810 Aug. 12	North Carolina coast	1810 Aug. 13 2000	Aug. 14 1700	−21	FM	1810 Aug. 14 0630	(15) p. 192.
255	1815 Sept. 3–5	New Bern and Beaufort, N.C.	1815 Sept. 2 1900	Sept. 3 0900	−14	NM	1815 Sept. 3 0200	(15) pp. 112–113.
256	1816 Sept. 23	Coastal North Carolina	1816 Sept. 21 1600	Sept. 21 1000	+6	NM	1816 Sept. 21 1300	(15) p. 194.
257	1831 June 10	St. Augustine and Atlantic coast of Florida.	1831 June 9 1400	June 10 0200	−12	NM	1831 June 9 2000	(15) p. 194.
258	1834 Sept. 4	South Carolina (especially Georgetown).	1834 Sept. 4 1900	Sept. 3 0951	−33	NM	1834 Sept. 4 0230	(15) pp. 121–122; (25d) National Weather Service No. 16, June 1975, p. 20.
259	1837 Aug. 16–20	Between N.E. Florida and North Carolina.	1837 Aug. 15 1900	Aug. 16 0100	−6	FM	1837 Aug. 15 2200	(15) p. 194.
260	1846 Sept. 7–9	Cape Hatteras Inlet and Outer Banks, N.C., especially Nag's Head.	1846 Sept. 4 1700	Sept. 5 0800	−15	FM	1846 Sept. 5 0030	(15) pp. 131–132; see also backwash tidal flooding aspects due to westerly winds noted in table 1.
261	1854 Sept. 7–8	Savannah, Ga.; Charleston, Port Royal, Beaufort, and Sullivans Island, S.C.; Sept. 10: Newark, N.J.	1854 Sept. 4 1100	Sept. 6 1618	−53	FM	1854 Sept. 5 1330	(15) pp. 132–134; (25d) National Weather Service No. 16, June 1975, p. 21 (Correction required in source: should read *Sept.* 7–8).

262	1861 Nov. 1–3.....	Cape Hatteras, N.C., northward to Jersey City and Newark, N.J.; New York City and Long Island, N.Y.; Newport, R.I.; Cape Cod, Boston, and New Bedford, Mass.; and Portland, Me.	1861 Nov. 2 1200	Nov. 2 1100	+1	NM	1861 Nov. 2 1130	(15) pp. 101–102.
263	1869 Sept. 8......	Cape Cod, Mass.; and southern New England	1369 Sept. 6 1500	Sept. 6 0100	+14	NM	1869 Sept. 6 0800	(15) pp. 101–108, especially p. 104, col. 2.
264 (15)	1869 Oct. 3–4.....	Grand Manan, Campobello, Deer and Mt. Desert Islands, Eastport, Calais, and St. Andrews, Me.; to New Brunswick, Canada.	1869 Oct. 5 0200	Oct. 5 0900	−7	NM	1869 Oct. 5 0530	(15) pp. 108–111, especially p. 110, col. 2, and p. 111; see also combination of extratropical and tropical storms in (15) p. 109, col. 1, and table 1, No. 15.
265	1874 Sept. 28......	South Atlantic coast, especially Charleston, S.C., and Savannah, Ga.	1874 Sept. 26 1300	Sept. 25 1700	+20	FM	1874 Sept. 26 0300	(70) 9/29/1874, p. 3, cols. 4–6, 9/30/1874, p. 1, col. 2.
266	1878 Oct. 23......	Richmond, Va.; Washington, D.C.; Cape May, N.J., and along Delaware River; Philadelphia, Pa.	1878 Oct. 25 0100	Oct. 25 1800	−17	NM	1878 Oct. 25 0930	(51) 10/24/1878, p. 2; (57) 10/24/1878, p. 1, cols. 2–3; (64) 10/25/1878, p. 1, col. 3.
267	1894 Sept. 27–28...	Georgia and the Carolinas..........	1894 Sept. 26 0032	Sept. 29 0044	−72	NM	1894 Sept. 27 1300	(17) p. 312.
268	1899 Aug. 17–21...	Cape Hatteras, N.C., etc............	1899 Aug. 20 1700	Aug. 21 0000	−7	FM	1899 Aug. 20 2030	(11) p. 164; (59) 8/18/1899, p. 1, col. 9.
276	1916 July 13–14...	South Carolina coast...............	1916 July 14 1900	July 15 0000	−5	FM	1916 July 14 2130	(17) p. 313.
277	1926 July 25......	New Jersey coast, especially Manasquan and Seagirt.	1926 July 26 0618	July 25 0013	+30	FM	1926 July 25 1500	(51) 7/25/26, p. 1, col. 5, p. 13, cols. 2–3.
281	1938 Sept. 21–22... (Became extra-tropical storm.)	Long Island, N.Y.; Providence, R.I.; and southern New England coastline.	1938 Sept. 20 1900	Sept. 23 1534	−69	NM	1938 Sept. 22 0530	(10) pp. 173–181, and illustrations following p. 184; (17) pp. 272–273.
283	1940 Sept. 2.......	Northern New England coast, Cape Cod, Mass.	1940 Sept. 3 0100	Sept. 1 2315	+26	NM	1940 Sept. 2 1200	(46) 9/2/40, p. 1, cols. 7, 8, p. 11, cols. 1–2.
286	1945 Sept. 18–19...	Atlantic City, N.J.................	1945 Sept. 22 2300	Sept. 21 1546	+31	FM	1945 Sept. 22 0730	(16) pp. 283–284.
288	1954 Sept. 11–12... (Edna)	Coastal areas from middle Atlantic States to New England, especially Long Island and southern New England.	1954 Sept. 14 1500	Sept. 12 1519	+48	FM	1954 Sept. 13 1500	(17) pp. 309, 310.
289	1954 Oct. 15...... (Hazel)	Morehead City and Wilmington, N.C.; Solomons, Md.	1954 Oct. 12 2100	Oct. 12 0000	+21	FM	1954 Oct. 12 1030	(17) pp. 245–257; (25d) National Weather Service No. 16, June 1975, p. 25; (27) April 1958, pp. 29–31; p. 30, col. 1, par. 2; (53) 10/15/54, p. 1, cols. 5–7, 8; 10/16/54, p. 1, cols. 1–3, 3–6, 7–8; p. 2, cols. 4, 7; p. 3, cols. 3–6.
290	1961 Sept. 21...... (Esther.)	Southern New York and New England.	1961 Sept. 22 2300	Sept. 24 0634	−32	FM	1961 Sept. 23 1500	(17) pp. 342–343; (25b) vol. 90, pp. 107–119.
295	1971 Sept. 30–Oct. 1. (Ginger)	Aurora, Cherry Point, New Bern, and Washington, N.C., as well as along Hatteras Banks and Pamlico Sound.	1971 Oct. 4 1000	Oct. 4 0700	+3	FM	1971 Oct. 4 0830	(25b) vol. 100, No. 4, pp. 256–267; (25c) HYDRO-27 Nov. 1975, p. 8.

*Cases in which the hurricane's principal flooding effects are within $\pm 3.5^d$ of the mean epoch of perigee-syzygy.

tainty the occurrence of true hurricanes in this early period of American history. Six factors contributed to this uncertainty:

1. In the 17th and 18th centuries, in which any definitive scientific knowledge of the origin and nature of hurricanes was lacking, it was a common practice to label as a hurricane, almost indiscriminately, any storm system accompanied by violent winds, inflooding tides from the sea, and catastrophic damage. A tendency toward flamboyancy and some exaggeration also occurs in the publication of early eye-witness accounts of these storms, which are characterized by a too frequent repetition of words describing each succeeding coastal flooding as "the greatest tide ever beheld in the memory of man," or a close paraphrase.

Accordingly, the use of the term "hurricane" in such early accounts—extending even into the mid-nineteenth century—is not necessarily reliable. This fact is especially obvious when, for example, it is stated in these contemporary records that an east coast hurricane occurred in mid- or high latitudes during the month of January, well out of the ordinary North Atlantic hurricane season running from June through October—although occasionally extending into May or November. (Some few examples of known deviations from this normal hurricane season are on record, but any such departures have occurred over tropical waters.)

2. While, in this early period, many sailing ships plied the hurricane-prone waters of the subtropical Atlantic and Caribbean, no expedient means of communication was available to convey a warning of any hurricane moving toward the east coast of North America before it hit the mainland. Meanwhile, an America-bound ship had either met disaster in the storm, had ridden it out, usually with accompanying damage and delay in arrival at its destination, or had been forced to return to a Caribbean port. Hence, in the relatively short period of time spanning the hurricane's landfall, subsequent onshore movement, and alongshore or offshore passage, there was no real way of establishing its tropical origin. A very intense extratropical storm formed offshore within a deepening low pressure center, or associated with a traveling wave along a cold front just off the coast, and affecting the coastal regions successively from Cape Hatteras north, might easily have been called a hurricane in this early period. The high-velocity winds common to the type of storm system today known as a nor'easter, which frequently invades all parts of New England from off the coast, likewise could have been confused with the similar winds characteristic of a hurricane.

3. Whether various of those early storms designated as hurricanes on the basis of apparent wind velocity and damage produced actually possessed winds of the sustained 74 mph required according to the present-day classification system is a matter of open conjecture. A revolving-cup wind instrument (anemometer) capable of recording continuous wind velocities (but still relatively inaccurate, and breaking down at extreme velocities) was not designed, in practical form, until 1846 (by T. R. Robinson).

4. No method was available in this country prior to January 1, 1871 (the date of the first U.S. synoptic weather map) to represent regional weather data by compiling simultaneously recorded weather observations on standardized chart formats. Accordingly, until this time, there were also no means of tracing the origin of a landfalling weather disturbance except, after the fact, from the reports of ships which had traversed the area during the period of its formation.

5. A frequent tendency therefore existed to consider a disproportionately large number of such cases of extremely active coastal storms to be of "tuffoon" nature, and to label them unqualifiedly as hurricanes. An unfortunate inclination also continued, in the case of those storms which had been wrongly described as hurricanes in earlier literature, to let these initial designations stand.

6. Often, in this early period, such intense storm systems may have been arbitrarily defined as hurricanes because of their severe coastal flooding effects. The designation was given without any allowance for the perigean spring or ordinary spring tides which might have been present. And, of course, such early terminology was assigned without any consideration to a minimum wind velocity requirement in accordance with the modern classification of a hurricane.

With these nomenclatural aspects of hurricanes thus historically evaluated, it should be clearly stated that there is no intention, in the present work, to discriminate subjectively between (1) hurricanes (table 2) or (2) offshore storms (table 1) as contributing causes to coastal flooding when either of these two weather phenomena occurs in conjunction with perigean spring tides. The emphasis on winter storms in this volume revolves around the fact that the flooding aspects of hurricanes already have been more adequately treated in other published sources. Under the appropriate conditions, both types of storms are strongly conducive to tidal flooding.

However, as confirmed in the accompanying bibliographic search (see part I, chapter 4) and the bibliography at the end of this work, the effects of a coincidence between either of these wind-intensifying situations and the astronomical tide-enhancing phenomenon of perigee-syzygy have not been discussed definitively anywhere in the scientific literature. Further, the greater length of time a winter storm is active near any one coastal location due to a generally slower velocity of forward movement compared with that of a hurricane actually provides, in the average case, a greater potential for tidal flooding. The hurricane center's movement over the sea surface is, in general, relatively fast, and the flooding influence more transient.

Table 3

Representative Cases of Coastal Flooding Occurring Near the Times of Ordinary (Syzygian) Spring Tides, Coexistent With Strong, Sustained, Onshore Winds

Explanatory Comments

As described later in the text (part II, chapter 7), a considerably greater statistical probability exists at ordinary spring tides than at the times of perigean spring tides for the coincidence therewith of strong, persistent, onshore

TABLE 3.—*Representative Cases of Coastal Flooding Associated* With Ordinary Spring Tides, Coupled With Strong, Persistent, Onshore Winds*

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Type of Syzygy	Reference Sources for Flooding (See key at end of table 4d.)
319	1878 Sept. 11	Along tidewaters of Savannah and Ogeechee Rivers, Ga.	1878 Sept. 26 1500	Sept. 11 1437	FM	(52) 9/12/1878, p. 3, col. 3.
321	1885 Feb. 16	New York, N.Y.	1885 Feb. 26 0624	Feb. 15 0912	NM	(51) 2/17/1885, p. 1, col. 7; p. 2, col. 1.
322	1889 Sept. 10	New York, Rockaway Beach, Seaside, and Coney Island, N.Y.	1889 Sept. 5 2006	Sept. 9 0842	FM	(51) 2/11/1889, p. 1, cols. 5–7.
338	1914 Dec. 7	Atlantic City, N.J., and New Jersey coastline; Far Rockaway, Coney Island, Arverne, and Sea Gate, Long Island, N.Y.	1918 Dec. 15 0912	Dec. 2 1321	FM	(51) 12/8/14, p. 1, col. 1; p. 7, cols. 3–6.
348	1925 Dec. 2–3	Coasts of New Jersey and New York; Long Island Sound; Coney Island, Bath Beach, Brighton Beach, and the Rockaways, Long Island, N.Y.	1925 Nov. 19 1436	Nov. 30 0311	FM	(51) 12/4/25, p. 1, col. 6; p. 2, cols. 2–3.
349	1926 Oct. 25 †	New York, N.Y	1926 Oct. 19 1000	Oct. 21 0015	FM	(51) 10/26/26, p. 1, cols. 2–4; p. 3, cols. 2–3; p. 16, cols. 2–5.
350	1927 Feb. 19–20	Cape May, N.J., to Cape Cod, Mass.; Atlantic City, Perth Amboy, South Amboy, Morgan, and Long Beach, N.J.; New York City and Long Island Sound, N.Y.	1927 Mar. 4 0512	Feb. 16 1118	FM	(51) 2/21/27, p. 1, col. 8; p. 2, cols. 1–6; 2/22/27, p. 1, col. 5; p. 3, cols. 2–3.
354	1929 Oct. 2	Barnegat lighthouse near Barnegat City, N.J.; coast of New York; along Long Island Sound.	1929 Sept. 27 1942	Oct. 2 1719	NM	(51) 10/3/29, p. 1, col. 1; p. 2, cols. 3–6.
359	1932 Oct. 19	Boston, Mass.	1932 Oct. 30 0918	Oct. 14 0818	FM	(51) 10/20/32, p. 44BQ, cols. 5, 6.
361	1933 Feb. 9	Sandy Point, Newfoundland	1933 Feb. 18 0542	Feb. 10 0800	FM	(51) 2/10/33, p. 1, col. 1.
367	1937 Apr. 27	Ocean City and north coast of N.J.; Far Rockaway and south coast of Long Island, N.Y.	1937 May 10 1300	Apr. 25 1024	FM	(51) 4/28/37, p. 14, col. 4.
368	1938 Oct. 28	West Wildwood, N.J	1938 Oct. 16 0300	Oct. 23 0342	NM	(51) 10/29/38, p. 21, col. 4.
369	1939 Sept. 26	Long Beach, Long Island, N.Y	1939 Sept. 12 1300	Sept. 28 0927	FM	(51) 9/27/39, p. 20, cols. 1–4.
370	1939 Nov. 25	Bay Shore, Fire Island Beach, Point o'Woods, Saltaire, Long Island N.Y.	1939 Dec. 3 0200	Nov. 26 1654	FM	(51) 11/27/39, p. 1, col. 2.
373	1947 Nov. 12	Cape Cod, Mass.	1947 Nov. 3 0900	Nov. 12 1501	NM	(51) 11/13/47, p. 29, col. 7; 11/14/47, p. 46, col. 2.
375	1949 Feb. 25	Redondo Beach, Calif.	1949 Feb. 14 0500	Feb. 27 1555	NM	(51) 2/25/49, p. 47, col. 5; 2/26/49, p. 8, col. 5.
376	1950 Nov. 26	Boston and Winthrop, Mass.	1950 Dec. 8 2000	Nov. 24 1014	FM	(25e) HYDRO–32, pp. 8–9; (51) 11/27/50, p. 16, cols. 2–6.
378	1953 Nov. 7	Southern New Jersey; Oakland Beach, Staten Island, N.Y.; Southport Beach, Conn.; and south coast of New England.	1953 Nov. 18 1800	Nov. 6 1258	NM	(51) 11/8/53, p. 1, cols. 2–8; p. 40, col. 1; p. 42, cols. 1–4.

See footnotes at end of table.

TABLE 3.—*Representative Cases of Coastal Flooding Associated* With Ordinary Spring Tides, Coupled With Strong, Persistent, Onshore Winds*—Continued

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Type of Syzygy	Reference Sources for Flooding (See key at end of table 4d.)
379	1955 Oct. 14	Lowland coastal regions from Cape Hatteras to Maine, including Staten Island, N.Y.; and entire Connecticut shoreline.	1955 Oct. 5 0600	Oct. 15 1432	NM	(51) 10/15/55, p. 1, col. 1; p. 34, cols. 2–4.
380	1956 Jan. 10	Cape May, Atlantic City, and along north shore and Raritan Bay, N.J.	1955 Dec. 28 1900	1956 Jan. 12 2201	NM	(51) 1/11/56, p. 33, cols. 2–4.
381	1956 Apr. 11	Norfolk and Hampton Roads, Va.	1956 Apr. 15 1700	Apr. 10 2139	NM	(25e) HYDRO–32, p. 8.
398	1973 Oct. 29	Monmouth Beach, N.J., to northern New Jersey and the Rockaways, N.Y.	1973 Oct. 15 2000	Oct. 25 2217	NM	(51) 10/30/73, p. 1, cols. 5–7; p. 47, cols. 3–6.
	Spring Tides, Plus Hurricane:					
351	1927 Aug. 25	From Delaware Breakwater to Cape Cod	1927 Aug. 15 1042	Aug. 27 0146	NM	(51) 8/25/27, p. 3, col. 1.
372	1947 Oct. 15	Savannah and Savannah Beach areas, Ga.; Georgia and South Carolina coast.	1947 Oct. 9 1300	Oct. 14 0110	NM	(51) 10/16/47, p. 31, col. 1.

*Tidal flooding occurring within $\pm 2^d$ of syzygy (difference taken in sense Fl.-S.) or—for those cases of greater separation—always *following* and (allowing for phase lag), within $+3.5^d$ of the time of the highest semimonthly spring tide. For all cases noted, the perigee-syzygy interval also is $>84^h$ (3.5^d), the upper limit for even pseudo-perigean spring tides.

†Actually, a case of pseudo-perigean spring tides ($P-S=-38^h$) but with the flooding occurring 5 days after the mean epoch of perigee-syzygy, and closer ($+4^d$) to the time of syzygy.

winds and their contribution to coastal flooding. The reason is that the phenomenon of syzygy occurs twice in each synodic month (new moon and full moon) or approximately 25 times in each calendar year. This frequency of disposition must be compared with the usual occurrence of only 2 cases of perigee-syzygy in each year which possess separation-intervals of ± 12 hours or less (or, at most, 5 cases which have separation-intervals of up to ± 24 hours. The possible range of opportunity for securing the coincidence of a sustained, strong, onshore wind is proportionately greater at syzygy alone than at perigee-syzygy.

Despite this fact, the number of cases actually recorded involving severe tidal flooding at times of ordinary spring tides is far less in terms of justified proportion to those produced at times of perigee-syzygy. This is because of the greater tidal amplification occurring from the combined alignment of perigee-syzygy, and the resulting increased potential for tidal flooding if the necessary supporting meteorological conditions are also present. A representative group of examples of coastal flooding accompanying ordinary spring tides is given in table 3.

One further lunisolar configuration is deserving of comment in connection with its relative tide-raising forces. This is the situation in which the Moon, while located at its perigee and closest monthly approach to the Earth, is simultaneously at its greatest possible orbital angular distance from either of the two syzygies (i.e., at one of its two positions of quadrature). The resulting tides produced (called *perigean neap* tides) are always of much smaller amplitude and range than perigean spring tides.

Thus, even in the presence of strong, persistent, onshore winds, it is an uncommon circumstance in which major tidal flooding accompanies perigean neap tides. Instances of coastal inundation at such times are correspondingly rare throughout history, unless extraordinarily high winds associated with an active coastal storm or a severe landfalling hurricane have prevailed.

However, for the record, a typical prototype of one such flooding tide uplifted by an unusually strong, onshore wind was that which took place on 1894 April 11 along the coastline of New York State (as recorded on page 1, col. 2 of the *New York Times* for April 12). In this month, perigee occurred on April 10 at 2244^h e.s.t. (the additional lag due to parallax age before the peak of the high waters was reached being approximately 1.5 days). The first-quarter moon occurred on April 12 at 1933^h e.s.t. Under the force of a strong, northeasterly gale, tidal flooding was experienced at such locations as New Brighton, South Beach, and St. George, Staten Island, and at Riverhead and Babylon on Long Island, N.Y.

Tables 4a–4d

Miscellaneous Factors of Dynamic Influence Associated With Perigean Spring Tides, in Cases Variously Lacking, or Reinforced by, the Presence of Strong, Persistent, Onshore Winds

Explanatory Comments

Tables 4a–4d quantitatively depict four supplementary but revealing tidal phenomena associated with the prediction of perigean spring tides. These are:

(a) the attainment of water levels of record-establishing height for astronomically produced tides (the correspondingly named *highest astronomical tide* for the locality) at the times of perigee-syzygy;

(b) The creation of extreme low waters of record, produced by the same amplified gravitational forces at the low-water phases of these tides;

(c) The occurrence of cases in which extraordinarily high waters are raised near the times of perigee-syzygy, but do not actually produce flooding of themselves because of insufficiently strong supporting winds. However, at high-water phase, they effectively block the hydrological runoff created by heavy precipitation, ice and snow melt, or similar freshets on the land. The result is a greatly augmented flooding of the coastal regions. The same type of flooding situation may occur as the result of tidal blocking of storm drains or elevated sewerage outfalls—even those supposedly remote from the land; and

(d) The production of conditions unmarked by severe flooding of the coast, but accompanied by extreme scouring and erosion of beaches, berms, estuaries, and inlets along wide stretches of the shoreline.

Table 4a.—*Representative Cases of the Highest High Waters of Record Observed at Various Tidal Stations, Within 2 Days of Perigee-Syzygy*

(Resulting from astronomically induced perigean or pseudo-perigean spring tides, *without* coincident strong onshore winds or significant coastal flooding.* See table 1 for wind-supported cases of tidal flooding.)

Date	Place	Extreme High Water (ft >MHW)	Perigee Minus Syzygy (h)	Mean Epoch of Perigee-Syzygy (75° W.)
	ATLANTIC COAST			
[1932 Mar. 24	Clarks Point, Mass	2.1	+21	Mar. 22 1730
1932 Apr. 21]	Rockland, Me	2.4	−1	Apr. 20 1530
1940 May 20	Boston Light, Lighthouse Island, Mass	2.3	−67	May 19 2330
[1942 May 31	Bath, Me	1.9	+9	May 30 0530
1942 June 29]	Bath, Me	1.9	−11	June 28 0130
1952 Aug. 5	Boston Light, Lighthouse Island, Mass	2.3	+20 *min.*	Aug. 5 1530
[1953 Feb. 15	Bar Harbor, Me	3.9	+9	Feb. 14 0030
1953 Apr. 13]	Deer Island (Fort Dawes), Mass	3.3	−37	Apr. 12 2030
1954 June 2	Port Clyde, Me	3.0	−39	May 31 0330

Date	Place	Extreme High Water (ft >MHHW)	Perigee Minus Syzygy (h)	Mean Epoch of Perigee-Syzygy (75°W.)
	PACIFIC COAST			
1927 Oct. 13	Seward, Alaska	4.1	+7	Oct. 10 1930
1936 Dec. 27	Santa Monica, Calif	2.3	−55	Dec. 26 1930
1945 Oct. 22	Skagway, Alaska	5.8	+8	Oct. 21 0500
1948 Jan. 25–26	Los Angeles, Calif	2.2	+4	Jan. 26 0400
1951 Jan. 5–6	Sweeper Cove, Adak Island, Alaska	2.6	−31	Jan. 6 2330
[1951 Nov. 30	Neah Bay, Wash	4.0	+36	Nov. 29 1400
1951 Dec. 29]	Crescent City, Calif	3.1	+11	Dec. 28 1230

* *Note:* The east coast cases cited also occurred prior to the great mid-Atlantic coastal storm of March 6–7, 1962. This event, in the combination of meteorological and astronomical effects, set many new tidal height records and was accompanied by major coastal flooding (see table 1 and chapter 7). Note the cyclical perigee-syzygy relationship between four pairs of these maximum high tides, bracketed above.

TABLE 4b.—*Representative Cases of the Lowest Low Waters of Record Observed at Various Tidal Stations, Within 2 Days of Perigee-Syzygy*

Date	Place	Extreme Low Water (ft <MLW)	Perigee Minus Syzygy (h)	Mean Epoch of Perigee-Syzygy (75°W.)
	ATLANTIC COAST			
1908 Feb. 2	Port Hamilton, N.Y	−4. 1	−8	Feb. 2 0000
1928 Mar. 23	Solomons, Md	−2. 2	+39	Mar. 22 1030
1934 June 28	Southport, N.C	−1. 9	+20	June 27 1000
1936 Mar. 24	Miami Beach, Fla	−1. 4	+5	Mar. 23 0130
1940 Jan. 24	Fernandina Beach, Fla	−3. 7	−36	Jan. 25 1200
1940 Mar. 24	Willets Point, N.Y	−3. 8	−10	Mar. 23 1000
	Boston, Mass	−3. 5		
1943 Jan. 7	Eastport, Me	−4. 2	−37 *min.*	Jan. 6 0730
1953 Feb. 15	Charleston, S.C	−2. 8	+9	Feb. 14 0030
1954 Dec. 11	Morehead City, N.C	−1. 7	−23	Dec. 9 0830
1955 Nov. 30	Portland, Me	−3. 5	+19	Nov. 29 2130
	Portsmouth, N.H	−3. 2		
1959 May 23	Eastport, Me	−4. 2	−8	May 22 0400

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Table 4b.—*Representative Cases of the Lowest Low Waters of Record Observed at Various Tidal Stations, Within 2 Days of Perigee-Syzygy*—Continued

Date	Place	Extreme Low Water (ft <MLLW)	Perigee Minus Syzygy (h)	Mean Epoch of Perigee-Syzygy (75°W.)
PACIFIC COAST				
1916 Jan. 4	Seattle Wash	−4.6	−15	Jan. 4 1630
1919 Dec. 8	Ketchikan, Alaska	−5.2	−7	Dec. 7 0130
1930 Jan. 14	Seward, Alaska	−4.3	+2	Jan. 14 1800
1930 Jan. 16	Astoria, Oreg	−2.8	+2	Jan. 14 1800
1932 Dec. 26	Los Angeles, Calif	−2.6	−33	Dec. 26 1330
	San Francisco, Calif	−2.5		
1933 Dec. 17	San Diego, Calif	−2.6	+9	Dec. 17 0230
	La Jolla, Calif	−2.5		
	Los Angeles, Calif	−2.6		
	Santa Monica, Calif	−2.5		
	San Francisco, Calif	−2.5		
1936 Nov. 29	Neah Bay, Wash	−3.6	−26	Nov. 27 2200
1937 Dec. 17	San Diego, Calif	−2.6	−5	Dec. 17 1130
1947 Jan. 7	Friday Harbor, Wash	−3.9	−16	Jan. 6 1600
1950 Nov. 11	Sweeper Cove, Adak Island, Alaska	−2.9	+14	Nov. 10 0100
Nov. 12	Massacre Bay, Attu Island, Alaska	−2.5	+14	Nov. 10 0100
1951 June 19	Sitka, Alaska	−4.0	+1	June 19 0800
1951 Dec. 29	Yakutat, Alaska	−4.3	+11	Dec. 28 1230
1955 May 22	Crescent City, Calif	−2.7	+7	May 21 1930
1957 Jan. 16	Ketchikan, Alaska	−5.2	+16	Jan. 16 0900
	Sitka, Alaska	−4.0		
	Skagway, Alaska	−6.7		
	Juneau, Alaska	−6.6		
	Yakutat, Alaska	−4.3		
1959 Dec. 30	Ketchikan, Alaska	−5.2	−18	Dec. 29 0500

TABLE 4C.—*Examples of Perigean Spring Tides Resulting in, or Contributing to, Coastal Flooding Through Impaired Hydrological Runoff*

Key No.	Date of Flooding	Location of Flooding	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Reference Sources for Flooding (See key following table 4d.)
458	1932 Mar. 24	Boston, Mass.; New York, N.Y.	1932 Mar. 23 0400	Mar. 22 0700	+21	FM	1932 Mar. 22 1730	(46) 3/29/32, p. 1, cols. 6–8, p. 6, cols. 2–5; (51) 3/29/32, p. 1, cols. 4–5, p. 4, cols. 2–5.
466	1936 Mar. 21	Newburyport and tidewaters of Merrimack River, Mass.; also, on March 19: Kennebec and Augusta, Me.	1936 Mar. 23 0400	Mar. 22 2300	+5	NM	1936 Mar. 23 0130	(40) 3/19/36, p. 1, cols. 7–8; Pictorial Review (14 pp.); (74) MKR–I, XIII, pp. 89–93.
469	1940 May 22	Norfolk, Va.	1940 May 18 1400	May 21 0833	−67	FM	1940 May 19 2330	(58) 5/23/40, p. 13, col. 5.
478	1952 Aug. 5	Boston, Mass.	1952 Aug. 5 1500	Aug. 5 1440	+20 *min.*	FM	1952 Aug. 5 1500	(46) 8/6/52, p. 1, cols. 2–6; p. 24 (illustrations).
86	1962 Oct. 13	Pacifica, Calif.	1962 Oct. 12 2300	Oct. 13 0800	−9	FM	1962 Oct. 13 0330	(31) 10/18/62, pp. 1–3, 6–8.

TABLE 4d.—*Illustrative Cases of Coastal Erosion Produced at Times of Perigean Spring Tides Coincident With Strong, Persistent, Onshore Winds*

Key No.	Date of Erosion	Location of Erosion	Nearest Perigee Date	Nearest Syzygy Date	Separation-Interval: Perigee Minus Syzygy (h)	Type of Syzygy	Mean Epoch of Perigee-Syzygy	Reference Sources for Erosion (See key following table 4d.)
K–87	1962 Nov. 10–14	Fire Island to Montauk Point, Long Island, N.Y.	1962 Nov. 10 0900	Nov. 11 1704	−32	FM	1962 Nov. 11 0100	(51) 11/15/62, p. 39, col. 8.
489	1967 Jan. 27–28	East side of Plum Island, Mass.	1967 Jan. 28 1000	Jan. 26 0141	+56	FM	1967 Jan. 27 0600	(29) pp. 52, 250, 256, 259.
490	1967 May 25–26	East side of Plum Island, Mass.	1967 May 21 2100	May 23 1523	−42	FM	1967 May 22 1800	(29) pp. 248, 251.
491	1969 Feb. 15–16	South spit of Pawleys Island, S.C.	1969 Feb. 13 2300	Feb. 16 1126	−60	NM	1969 Feb. 15 0500	(21) p. 6.
492	1969 July 29	Closure of existing south inlet of Pawleys Island, S.C., by erosion, and creation of a new inlet farther north.	1969 July 28 0400	July 28 2200	−18	FM	1969 July 28 1300	(21) p. 6.
N–99	1974 Jan. 8	Recreational beaches at Oceanside, Calif.	1974 Jan. 8 0600	Jan. 8 0800	−2	FM	1974 Jan. 8 0700	(32) 1/19/74, local news section.

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Table 5

A Representative Sample of Newspaper Articles Covering Tidal Flooding Events Associated with Perigean Spring Tides, 1723-1974

Explanatory Comments

The following reproductions of news articles, covering 50 major tidal flooding events that have occurred on both the east and west coasts of North America in association with perigean spring tides, comprise one-half of the total list of representative events listed in the master catalog (table 1). In practically all cases, considerable additional information was contained in the original full-length news article. These news accounts have been shortened, and considerable detailed material relating to individual property losses as the result of tidal flooding has been deleted. The excision of material is indicated by the use of ellipses. News photos which, in many cases, accompanied the original stories and illustrated the considerable extent of flooding damage have been eliminated, for technical reasons.

However, no substantive editing involving any alteration of the original content has been employed. Every attempt has been made to preserve all possible information on the preceding and concurrent meteorological conditions pertinent to the tidal flooding, the observed and recorded heights of the tides, and other factual data. Care also has been exercised to include all newspaper datelines or, where these are lacking, other textual references to the time of the flooding event (the day of the week, etc.) through which an accurate correlation may be made with the corresponding perigee-syzygy data.

The exact source of each article is identified by newspaper name, day of the week and date of publication (or the period of coverage for weeklies), and the page and column for each article used. The initials "O.S." stand for Old Style Calendar and "N.S." for New Style Calendar, whose exact meanings are explained in a technical note at the beginning of chapter 1. (References to columns start with that at the extreme left hand side of the page as col. 1 and proceed progressively to the right.) Although newspapers may have changed their titles over subsequent years, the contemporary title is used in all cases. The articles are chronologically arranged.

The boldface number following each newspaper article is a key number for use in cross-referencing the article to the listing of the flooding events and their associated astronomical conditions given in table 1, where the same serial numbers are used.

The presence of a capital letter preceding this number indicates that a corresponding synoptic weather map and/or tidal curve relating to this event (and carrying the same alphanumeric descriptor) are to be found in part II, chapters 7 and 8, respectively, of the text. Where tidal flooding occurred simultaneously on both the east and west coasts, a small letter "e" or "w" following the key number indicates which coast is represented.

The figures printed in the lower left corner following each news article provide information relating to the perigee-syzygy alignment with which the reported tidal flooding was associated. The first such entry gives the date and time of the mean epoch of perigee-syzygy, specified to the nearest hour or half-hour in the respective eastern standard time (e.s.t.) or Pacific standard time (P.s.t.) zone concerned. All times given are standard times, despite the occasional historical intervention of daylight time or war time. The number in parentheses is the separation, in hours, between the times of perigee and syzygy, in the algebraic sense perigee minus syzygy. This grouping of data conforms exactly with the data given in similar slant-lettering on the reproduced synoptic weather maps, tide curves, or other graphical representations throughout the volume, with which these data may be rigorously compared.

The morning-final or evening-final editions of the newspapers concerned were used in nearly all cases. Where another edition was used and this fact is known, it is so indicated. Since many of the original newspaper articles were not reproducible in their aged condition, all articles have been uniformly reset, in abridged form. Although some of the earliest news accounts lack headlines, and other such heads have been eliminated because of their multiple-column widths or large point sizes, an effort has been made to retain significant headings wherever possible.

Additional news articles relating to unusually large coastal flooding events which are given special attention in the main body of the text are contained in chapter 7.

The Boston News-Letter (New England - Weekly)
Thurs., Feb. 21-Thurs., Feb. 28, 1723 (O.S.)
Page 2, Col. 2

Boston, Febr. 25.— Yesterday, being the Lord's Day, the *Water* flowed over our Wharff's and into our Streets to a very surprizing height. They say the *Tide* rose 20 *Inches* higher than ever known before. The *Storm* was very strong at *North-east* . . .

. . . The loss and damage sustained is very great, and the little Image of an *Inundation* which we had, look'd very dreadful . . .

1722/23 Feb. 23 (O.S.)
1723 Mar. 6 (N.S.)
16h e.s.t. (−6)

4

The Boston Gazette and Country Journal
Mon., Dec. 11, 1786 (N.S.)
No. 1690, Page 3, Col. 1

Boston, December 11.—On Monday evening last came on, and continued without intermission until Tuesday evening, as severe a snowstorm as has been experienced here for several years past . . .

. . . The wind, at east, and northeast, blew exceeding heavy, and drove in the tide with such violence on Tuesday, as overflowed the pier several inches, which entering the stores on the lower part thereof, did much damage to the Sugars, Salt, &c. therein—considerable quantities of wood, lumber, &c. were carried off the several wharfs . . .

1786 Dec. 4
23.5h e.s.t. (−17)

7

The Philadelphia Inquirer
Thurs., Oct. 24, 1878
Page 1, Cols. 2, 3

High Tide at New York and Shattered Shipping, Docks and Buildings.

New York, Oct. 23—The tide which accompanied the eastern gale of today was one of the highest remembered, and caused extensive damage along the city's eastern front. The sea walls around Ward's, Randall's and the upper end of Blackwell's Islands were submerged by the waves, and many docks were so badly shattered that it will be necessary to rebuild them. The Harlem flats resembled an inland sea . . .

. . . The tide rose to a great height and washed out many manufacturing places . . .

. . . Much damage was done to buildings by the wind, and to the docks by the very high tide. The meadows between Williamsburg and Greenpoint were flooded by the wind backing the water up East river, and a number of buildings were inundated . . .

1878 Oct. 25
9.5h e.s.t. (−17)

19

The New York Times
Fri., Sept. 29, 1882
Page 5, Col. 2

HIGH TIDES AT LONG BRANCH

Long Branch, Sept. 28.—The storm on the New Jersey coast has increased in intensity since midnight yesterday, the gale continuing from the north-east . . .

. . . At high tide this morning—8:30 o'clock—a terrific sea was coming over the Long Branch Ocean Pier, the black waves touching the floor of the pier 20 feet above the ordinary tide . . .

. . . The heavy sea washed over the land and into the Shrewsbury River, the water reaching the first floors of the elegant cottages and flooding the stables. Carriages were sent to higher ground on the mainland. The Pennsylvania Railroad was badly cut at Seaside Park, and passengers were sent by way of the New-Jersey Central to New-York. At Branchport, Little Silver, and Red Bank at low tide the waters were within eight inches of the floors of bridges, and much alarm was felt as to the effects of the high tide to-night. This tide is the highest ever known here . . .

. . . The high tide of yesterday morning has not been surpassed in several years. Late last evening the tide was rising rapidly, and there was every indication that this morning it will reach the same height as yesterday, if it does not surpass it . . .

1882 Sept. 26
19h e.s.t. (−10)

20

The Boston Herald
Wed., Nov. 25, 1885
Page 1, Cols. 4–6

A MIGHTY TIDE.

Old Neptune Baptizes the Shore.

An Unprecedented Rise of Water.

Picturesque Commingling of Wind and Wave.

Great Damage to Property in New York.

The Jersey Coast Strewn with Wreckage.

. . . Yesterday's storm proved one of the severest that has visited this section of the country, its effect being most perceptible along the coast and water front of the city. In the upper harbor at noon, when the tide was full, the sight was a grand one . . .

. . . At the South city ferry the tide overflowed to the entrance gates on Lewis street on the East Boston side, and the Eastern-avenue entrance in the city proper was all awash for a short time. The ticket boxes on the East Boston side were submerged to the depth of several inches by the encroaching element. At the North ferry the extreme high tide made matters unpleasant for the pedestrians, as the water worked its way up through the easterly end of the new headhouse on the Boston side. The ferry employes say that the tide was the highest that has been known here for a great many years. The tide at midnight was considerably higher, it rising 11 ft. 7 in., but owing to the decrease of the wind, its effects were not so severe as those of the noon tide . . .

. . . The waves at noon broke over the high wall of the State dock, South Boston, and sent their spray high in air, the foam from which was blown several hundred feet inland. The sea wall between Jeffries point and Wood island, which has

Towered Above the Angry Waves

since the destructive gale which washed Minot's light away in 1851,—was yesterday overtopped by the briny elements, and large sections of it were wholly submerged, while on all parts the sea made heavy breaks at frequent intervals . . .

Along the North and South Shores.

The tides ran unusually high at Lynn. There was much damage at some of the wharves. The water nearly reached the Nahant roadway. The Boston, Revere Beach & Lynn railroad's outward tracks were badly washed for a fourth of a mile between the Point of Pines and Oak Island . . .

The tide was the highest at Salem that has been known for years. It filled the North river canal to the top.

The tide at Edgeworth and in the marsh on Charles street was the highest ever known. A large number of cellars were flooded, and a lot of lumber floated off. The water covered the Saugus branch track of the Boston & Maine railroad, causing some inconvenience to trains. The tide also covered Charles street, making it impassable. A large number of tons of hay was floated off on the marshes at Wellington, causing a considerable loss.

At Cohasset the tide was the highest since April 16, 1851, the day of the destruction of Minot's ledge lighthouse. The streets and meadows in the vicinity of the harbor were overflowed, and the wharves were covered to a depth of 18 inches.

NEW YORK AND VICINITY

Great Damage to Property—The Highest Tide Ever Known

New York, Nov. 24, 1885. Never before has such a high tide rolled in upon the city, and incalculable damage has been done along the water front. At 10 o'clock, when the tide was at the full, the water was said by the ferry authorities to be nearly three feet higher than it had ever been known before. The bridges in the ferry houses on the North river were tilted up by the tide to an angle of 30°, and the incoming boats scraped along on the top of the rack guards. When the boats were made fast to the docks, the passengers, in many cases, had to be hoisted upon the bridge . . .

. . . A telegram from Rockaway Beach says "Great damage has been done all along the beach. The tracks of the New York, Woodhaven & Rockaway railroad have been washed out, and trains cannot proceed. The spile work across Jamaica bay is totally submerged, and, for safety's sake, no trains are allowed to cross it. The docks at the different hotels have all been damaged, and are likely to break up entirely unless the wind shifts soon. The families living in small houses along the ocean and bay have been obliged to move out. The cellar of the great hotel is flooded. The wind is blowing a gale" . . .

. . . At Hunter's Point, the tide rose to an extraordinary height, water to the depth of several feet having covered the docks and street for a distance of a hundred yards, rendering foot travel to the ferries and railroad impossible. Wagons cannot get aboard the ferry boats, the latter being several feet above the ferry bridges. The lower parts of Astoria and Ravenswood are also flooded. The meadows at Flushing are under water, and the railroad trestle is covered in places. Several wagons and small outhouses have been carried off and are floating in the bay. The cellars and first floors in the lower part of the village are flooded, and the inmates of the houses have been compelled to move upstairs.

At Atlantic City, N. J., the tide was the highest for years. The damage to property was considerable. Much of the board walk along the ocean front is washed away, and the railroad tracks are washed out near the inlet. Many of the streets are flooded. Boats are being used to convey residents up and down some of the streets . . .

. . . From Barnegat bay to Sandy Hook the beach is covered with boards torn from bulkheads and summer houses. The ocean promenade and pavilions of James A. Bradley, the founder of Asbury Park, were damaged to the amount of $1000. Several elegant cottages at Elberon have been badly damaged.

At Bridgeport, Ct., the tide reached the highest point known in that vicinity for many years, wharves, warehouses and cellars along the water front being overflowed to the depth of several feet, causing much damage . . .

1885 Nov. 23
22h e.s.t. (+59)

21

The New York Times
Wed., Oct. 14, 1891
Page 1, Col. 5

DAMAGE BY HIGH TIDES

Long Branch, N. J., Oct. 13.—The severe northeast wind and rain storm which has been raging for the past twenty-four hours has done considerable damage all along the New Jersey coast, and particularly between Sandy Hook and Point Pleasant. For twelve hours the wind along the seaboard has blown from forty to fifty miles an hour and the sea has been unusually high and strong . . .

. . . The foundation and platforms of the Ocean Hotel bathing pavilions, just south of the pier, were this morning smashed into kindling wood by the high tide and carried out to sea. Between the Surf House, just north of the pier, and Chelsea Avenue nearly eight feet of sand have been carried away, and the bluff has been badly washed and inundated . . .

. . . Minugh's Hollow, at Seabright, is flooded by the high tide in the Shrewsbury River, and several small houses there have been badly undermined. The tide there is so high that the first floors in several houses are submerged. At Highland Beach the tracks of the New-Jersey Southern Railroad are covered with water . . .

. . . Point Pleasant, N. J., Oct. 13.—The high tide this evening cut the beach badly at Seabright. At this place the large pavilions of W. T. Streets and Dr. Knox were surrounded by water and both houses were washed away. The seas ran down all Atlantic and Arnold Avenues and the board walks are afloat. At Bayhead 300 feet of bulkhead and board walks were cut out and went to sea. At Barnegat City the railroad is torn up to the beach and railroad communication to the city is cut off. At Atlantic City and Ocean City the sea is very high, and the railroad from Cape May to Sewell's Point is under water. The sea came in like a tidal wave. It is the worst surf in years. . . .

1891 Oct. 16
23h e.s.t. (—20)

23

The New York Times
Sat., Feb. 9, 1895
Page 3, Col. 4

TREMENDOUS TIDES ON THE COAST

Wharves, Streets, and Buildings Flooded

. . . enormous high tides prevailed along the entire coast . . .

BIG TIDES ALONG NEW-ENGLAND.

Streets, Wharves, and Buildings Badly Flooded.

BANGOR, Me., Feb. 8.—The tide here today was the highest since the freshet of

1846. There is from one to three feet of water in the cellars of stores on Exchange, Broad, Central, and Front Streets. The damage caused is from $15,000 to $20,000.

The tide is five feet higher than flood. The railroad bridge across Kenduskeag stream is weighted down with freight cars and locomotives to prevent it from being carried away.

PORTLAND, Me., Feb. 8.—To-day's tide was the highest known here for years. In some cases the water rose to the flooring of the wharves, and it flooded many cellars.

BATH, Me., Feb. 8.—The tide to-day is the highest ever recorded here, necessitating the stopping of work in several buildings along the wharves.

PROVIDENCE, R. I., Feb. 8.—The tide at this port was the highest since the famous storm of September, 1869. The water ran over docks and wharves and submerged cellars of warehouses. In some parts of the Narragansett Electric Lighting Company's plant 6 feet of water were measured. The damage to the company will amount to thousands.

NEW-BEDFORD, Mass., Feb. 8.—The tide here was never known to rise so high as it did to-day. Water covers the wharves to the depth of two feet. Front Street was inundated to the depth of eighteen inches. On Water Street the New-Bedford Machine Company and the Smith & Carlton Iron Foundry were obliged to close, and several of the mills were forced to close down because of the large amount of water in the basement.

HIGHLAND LIGHT, Mass., Feb. 8.—Such a gale as swept Cape Cod to-day has not happened before since the great blizzard of 1888. The wind at 9 A. M. reached a velocity of sixty miles an hour.

The tides in the bay were higher than ever known before, washing the banks and threatening the destruction of twenty fishing houses along the shore. Roads were washed in every direction.

NEWPORT, R. I., Feb. 8.—A tremendous high tide, accompanied by great seas and heavy ice, is doing great damage along the water front to-day. Two barges are ashore.

At the beach, a part of the sea wall is gone, and the roadway is washed away. At the naval station, several thousand dollars' damage was done to walls.

1895 Feb. 9
10h e.s.t. (−4)

25

The New York Times
Sun., Feb. 10, 1895
Page 1, Cols. 3, 7

. . . SANDY HOOK, N. J., Feb. 9.—The large four-masted steamship Patria of the Hamburg-American Packet Steamship Company, while proceeding to sea this evening, grounded in the main ship channel, near the southern edge of Palestine Shoal . . .

LOWEST TIDE IN TWENTY YEARS

Ferryboats Blockaded by Ice—Few Lines in Operation.

A northwest wind, an extremely low tide—the lowest in twenty years, old boatmen say—and the heavy ice conspired yesterday to tie up all the ferries on the East River from the Battery to Thirty-fourth Street . . .

1895 Feb. 9
10h e.s.t. (−4)

25

The New York Times
Sun., Feb. 10, 1895
Page 2, Col. 1

. . . The Staten Island ferryboats were all running, but their trips to and from St. George were eventful. The Southfield had a severe encounter with an ice floe at 6 o'clock in the morning. She was on her first trip from Staten Island, and she had a number of passengers on board. She came up the bay without much trouble, but between Governor's Island and the Battery she got stuck in a heavy icefield that was swept by the current around from the North River into the East River toward the bridge. The Southfield tried hard to escape from the ice, but her wheels were clogged and she was forced to drift with the floe . . .

. . . The boats of the Staten Island line ran all day, but late in the afternoon the tide was so low that the ferry bridges were far above the decks of the boats, and the ascent and descent were so dangerous that teamsters did not dare to risk their horses on the steep planks, and wagon traffic had to be suspended . . .

. . . The Shackamaxon, that plies between Ellis Island and the Battery, made several trips, and every one was eventful. She encountered immense cakes of ice, through which she had to plow her way, and the northwest winds that swept in gales across the bay helped to impede her progress . . .

. . . The Fulton Ferry boats Fulton and Farragut ran until 4 o'clock yesterday afternoon. From 6 to 9 A. M. they had much difficulty in getting across, but after noon they made trips more regularly. At 4 P. M. the tide was so low and the ice on the Brooklyn side became so bad that it was necessary to stop running the boats . . .

1895 Feb. 9
10h e.s.t. (−4)

25

The Richmond (Va.) Dispatch
Fri., Aug. 18, 1899
Page 1, Col. 7

THE TIDE UNUSUALLY HIGH

NEWPORT NEWS, VA., August 17.—(Special.)—James river at this point is higher to-night than it has been since the great storm of 1889. It is believed the tide has risen five feet above average high water. The water is up in the car-tracks, in the bottom of the piers, and within a foot of the pier-floors . . .

1899 Aug. 20
20.5h e.s.t. (−7)

30

The New York Times
Mon., Nov. 25, 1901
Page 1, Col. 7

Heavy Tide Overflows East and West River Fronts.

. . . The northeast gale, that started to blow in this neighborhood Saturday evening, did not abate to any appreciable extent, until well in the afternoon of yesterday. Its maximum velocity was nearly sixty miles an hour. It blew with unabated fury all night Saturday and yesterday morning . . .

. . . Not only the winds made life miserable from a marine standpoint, but the tides as well. According to veteran mariners long familiar with everything that had to do with New York Harbor, a tide such as has not been seen in these parts in nearly a score of years washed upon the shores of the city and nearby islands yesterday morning. It swept over the Battery wall, deluged the piers along the river fronts, finally ending in the cellars under the houses on South, West, and other affected streets, soaking and in many cases ruining, the merchandise or other things contained in them . . .

. . . In Manhattan the greatest damage, of course, was along the streets fronting on the rivers and in the subway. On West Street produce merchants were busy bailing the water out of their cellars. From Warren Street to Park Place, on West Street, the shops, saloons, and restaurants were flooded. A restaurant at 165 West Street was so completely surrounded with water that the proprietor was unable to get to it when he arrived to open up early in the morning.

The Fall River steamer in arriving at Pier 18, at the foot of Murray Street, had to keep her passengers on board owing to the water, which was about two feet deep, that flooded the street outside. . . .

. . . In the East River there was a serious amount of damage, due to a tide, which river men insist has never been equalled in their experience. The lighthouse on the north end of Blackwell's Island, usually high above flood tide, was wrapped in spray, the platform of the house being but little above the water. The entire north side of the island was flooded at 9 o'clock, and several small frame buildings were carried away.

In the upper west side the greatest damage was in the rapid transit tunnel, the excavations extending through Lenox Avenue north from One Hundred and Thirty-fourth Street to the Harlem River . . .

. . . This trench is eighteen feet wide and forty feet deep, and is to go under the river at a depth of sixty feet below its bottom. The contractor had sunk a coffer dam at the river bank. This held, but the water poured over it and into the tunnel, filling it. The banks were softened and caved in at many places, but the tunnel is not seriously damaged. The loss to the contractors is about $10,000 . . .

1901 Nov. 25
15.5h e.s.t. (—9)

34

The New York Times
Mon., Nov. 25, 1901
Page 2, Cols. 3, 4

HAVOC AT KEYPORT

KEYPORT, N. J., Nov. 24.—The tide rose until the docks along the water front were several feet below the water. More than a hundred large sloops were in Keyport harbor, besides a large number of smaller craft. Owners of the vessels stood upon the shore this morning and were powerless to save their property, as the vessels dragged their anchors and burst from their moorings.

The tide and wind swept oyster boats and handsome sloops in a wrecked mass upon the shore and meadows. The Golden Gate, a large sloop owned by Capt. William E. Woolley of this place, was dashed upon the shore here, and crashed through a large storehouse building owned by Baner & Hopkins . . .

. . . Storehouses, docks, and bath houses were lifted from their foundations and carried away with the tides . . .

. . . Thomas Brown's dock at Lockport was almost completely wrecked by the tide . . .

MUCH DAMAGE ON THE CONNECTICUT COASTS.

NEW HAVEN, Conn., Nov. 24—At Shippan Point, in Stamford, several docks connected with Summer residences were carried away by the unusually high tide, and the cellars of a number of buildings near the water front were completely submerged. Along the canal the water rose over the banks and a considerable part of the lower end of the city was inundated. The freight offices of the North and East River Steamboat Company were flooded, as were many of the shops on the canal . . .

. . . Milford probably suffered more than any other town on the Connecticut shore, and the damage there is estimated at $10,000. The seawall at Burwell's Beach, recently built, was completely carried away. At Fort Trumbull Beach every bathing house was washed away, and the banks and lawns of the Summer homes were destroyed . . .

. . . At Greenwich the tide was five feet higher this morning than usual, and everything on the low lands was carried away. Lumber yards were flooded, and huge piles of lumber toppled over and floated out into the harbor. At Belle Haven two docks owned by John P. Laflin and John B. Barrett were swept away and carried on to Byram shore, and the macadam roads were damaged to such an extent that it will take from $3,000 to $4,000 to repair them. The total damage in this vicinity will reach at least $7,000 . . .

SCENES OF DESTRUCTION AT OLD CONEY ISLAND

Bulkheads and Boardwalks Smashed Into Kindling Wood.

. . . Coney Island breezes yesterday were of the cyclonic sort, and came from the northeast, meeting unusually high tides, so the waves rose high, worked havoc with the strongest bulkheads, and tossed about boardwalks with a playful madness rendering them fit only for kindling wood . . .

. . . The flood tide at 5:36 o'clock in the morning came tearing in and tearing up . . .

. . . The Manhattan Beach Hotel suffered severely on its water front. The plank walks were torn away, 610 feet being destroyed, and the bathing pavilion was very nearly destroyed. At the Oriental Hotel the boardwalk was torn to bits. The iron lamp posts were twisted and bent, and the embankment cut into. It will not be possible to fix the loss until the storm has subsided and an examination can be made. The waves breaking over what was the boardwalk rolled in on the lawn and scattered over it the debris of its earlier destruction. The total loss at Coney Island is estimated at $25,000 . . .

CHATHAM, Mass., Nov. 24.—The life savers along the shore from Monomoy Point to Provincetown report the gale as very severe, with a high tide which has washed away miles of the beaches and made bad inroads into the headlands. At South Beach the high tide and heavy seas have cut away the sand embankment for many years . . .

1901 Nov. 25
15.5h e.s.t. (—9)

34

The Evening Telegram
Saint John's, Newfoundland
Tues., Feb. 3, 1908
Page 4, Col. 2

. . . The railway track was washed away about eight miles this side of Port aux Basques so that the Bruce express was not able to leave there this morning. The sea swept in with terrific violence and inundated the track for several hundred yards. The tide is not expected to subside till this afternoon, about 3 o'clock . . .

1908 Feb. 2
0h e.s.t. (—8)

35

The Los Angeles Times
Fri., Dec. 18, 1914
Pt. 2, Page 1, Cols. 4, 5

Destructive.

SEAS LASHED BY GALE BATTER COAST TOWNS

Houses Destroyed, Bulkheads Shattered, Sewer and Gas Mains Severed by Pounding Breakers on Crest of High Tide—More Trouble Feared Today—Loss of Property Many Thousands—No Casualties.

Lashed to a fury by a heavy on-shore gale that lent impetus to an unusually high tide, the sea battered the southern coast early yesterday morning with fury and destroyed property worth many thousands of dollars.

From all along the shore came the same story, of huge waves leaping over barriers and carrying destruction with them. At Long Beach $80,000 damage was done, while at Balboa the loss was also heavy. Railway tracks were washed out at the harbor and traffic delayed for hours. One fatality due to the storm was reported from the sea. There were no casualties ashore.

The off-shore breeze that accompanied the rain of Wednesday night switched to the southeast early in the day, and blew at places forty-five miles an hour. No damage was done here.

Further trouble at coast points is feared for this morning's high-tide period.

TERROR AT LONG BEACH.

Washing houses into the sea, tearing up concrete bulkheads and cement promenades, and spreading terror and damage along the ocean front, the wind, aided in its work of destruction by an extremely high tide and heavy rain, paid a terrifying visit to Long Beach early in the morning. Many persons had narrow escapes from drowning in their seaside bungalows, one of which was completely destroyed, and four are partially washed away.

Great anxiety is felt along the washed-out portions of the beach over this morning's high tide, when more buildings and works are expected to go. A tide of 7.3 feet is expected at 9:15. Many of the houses on the east beach are hanging over a bluff caused by the waves, and, although the owners and occupants of these buildings worked feverishly last night with bags of sand and timbers, they cannot hope to stem the huge tide expected . . .

1914 Dec. 16
0h P.s.t. (−36)

38

The Los Angeles Times
Fri., Dec. 18, 1914
Pt. 2, Page 6, Cols. 3–5

PENINSULA INUNDATED.

In the wake of a forty-five mile gale, the tide rose to unprecedented height at Balboa Beach yesterday morning, broke over the bulkheads, cut 100 feet off the tip end of the peninsula, inundated Collins Island, damaged or wrecked a score of residences and receded, leaving many thousands of dollars damage in its wake . . .

. . . Although the storm was accompanied by a gale from the southeast and the highest tide in nearly twenty years, there was no damage to shipping at the harbor . . .

. . . The tide at 8:50 a.m. reached 7.5 feet, and with the storm behind it backed up the water in the channel and the bay to a hitherto-unknown height.

About 200 feet of the Salt Lake track at Ostend was washed out by the high tide, and train service was demoralized for several hours. Repairs were completed last night and service resumed . . .

1914 Dec. 16
0h P.s.t. (−36)

38

The Virginian-Pilot and the Norfolk Landmark
Norfolk, Va.
Sun., April 4, 1915
Page 5, Col. 3

STORM SEVERE AT VIRGINIA BEACH

. . . More damage was inflicted by the storm at Virginia Beach than that resort has suffered in the past 30 years. Swept by the 75-mile gale of Friday night and early yesterday morning, the beach front suffered in a number of places, both from wind and water . . .

. . . Practically all of the board walk in front of the site of the old Princess Anne hotel was torn up by the surf which broke over the sea wall . . .

1915 Mar. 31
22h e.s.t. (+42)

39

The New York Times
Thurs., April 11, 1918
Page 15, Cols. 5, 6

Sixty-Mile Blow from the East Piles Twelve-Foot Tide Over Piers and Streets.

Beach Hotels and Bungalows Flooded and New Cement Shore Walk Undermined

. . . A sixty-mile easterly gale, blowing directly from the sea, pushed a tremendous tide against the whole length of the south shore of Staten Island late yesterday afternoon, submerging piers from four to six feet, inundating streets and business property, and tearing several small vessels from anchorages and throwing them ashore. It was estimated that the property loss would reach $100,000 . . .

. . . All along the waterfront from Simonson Avenue, at Clifton to Fort Wadsworth, a distance of two miles, the piers were under water, and the ships which had been loading or discharging cargo had to be moved to outside anchorage last night to prevent them pounding to pieces. In Clifton the water was four feet deep in the streets, and boats were used to move about.

Summer hotels and bungalows at South

Beach and Midland Beach were damaged severely. The flood swept over the first floors of most of these places. Long stretches of the new concrete walk at both beaches were undermined by the tide . . .

. . . At 10 o'clock last night it was said the tide had reached eleven feet above normal high tide, the highest for years . . .

. . . SEABRIGHT, N. J., April 10.—Row boats were used in Ocean Avenue tonight at high tide. The crest came at 11:30 after which it subsided a little after threatening to inundate several buildings . . .

1918 Apr. 10
14.5h e.s.t. (−19)

A–43

The New York Times
Sat., April 13, 1918
Page 11, Col. 3

Unusually High Tide Drives Water to Station Entrances in Jersey City.

Homes at Sea Bright Inundated—$50,000 Damage at Sea Gate.

. . . The high east wind and the unusually high tide yesterday caused great damage all along the Atlantic Coast . . .

. . . On the waterfront the water piled up by the wind flooded streets, undermined houses, interfered with ferry traffic, and caused discomfort to thousands of persons. In New Jersey the water came up so high that it flooded the waiting rooms of the railroad stations and interfered with the handling of freight in the Erie and Pennsylvania railroad yards.

When the tide came up water began to run down the steps of the entrance to the Hudson tunnel in the Lackawanna station in Hoboken. It soon became so bad that the entrance had to be closed to the public, and a barricade of boards was hastily raised to stop the water from flooding into the tube and interfering with the traffic. As the tide came higher the water rose in the ferry houses and more poured into the tunnel . . .

. . . Wind and tide wrought destruction along the shore from Long Beach to Sea Gate. At Coney Island, Brighton, and Sea Gate the police last night estimated the damage at $50,000 . . .

. . . In the district around Far Rockaway streets were flooded, small buildings carried away, and larger ones damaged. Train and trolley service was practically stopped. Near Howard Beach parts of the Long Island Railroad tracks were covered by water. Families, fearing the water would rise above their living quarters, sought refuge in the upper stories. Finucan's Hotel, facing the sea, was so undermined by water that it was feared it would collapse. The boulevard at Edgemere was covered with water and several bungalows were washed away.

. . . According to the city gauge at Pier A, North River, at 10 o'clock Thursday night the card registered a height of water of eight and fifteen-hundredths feet above mean low water. This is the highest tide since the records were established in 1886 . . .

SEA FLOODS ATLANTIC CITY

ATLANTIC CITY, N. J., April 12.—A record tide did much damage along the sea front today. For the first time in years the sea flooded the lawns of the big hotels, smashed doors and flooded cellars, drowning out fires in some of the apartment houses and causing loss of property in store rooms. The water put the plant of the electric company out of service, and the entire city was in darkness last night.

1918 Apr. 10
14.5h e.s.t. (−19)

A–43

The New York Times
Mon., Nov. 25, 1918
Page 12, Col. 6

Remarkable Tides on Nov. 18

To the Editor of The New York Times:

Your issue of Nov. 19 contained this paragraph:

"The south wind caused an unusually high tide. Many of the ferry bridges were lifted until vehicles had to go up a sharp incline to make the boats, and in some cases the water flooded the ferry houses."

Your issue of the 20th reproduced a dispatch from Quebec, dated Nov. 19, which read in part as follows:

"The tidal wave . . . swept up the St. Lawrence last night, causing damage estimated at $1,000,000. Part of the village of Batiscan was submerged by the flood tide."

The above accounts went on to ascribe the abnormal tides to the south and east winds, which, of course, had an effect, but there were two other unmentioned causes —the moon, and the low barometer pressure.

The moon was full Nov. 19, and it is a familiar phenomenon that, other things being equal, tides always run higher and run lower at full moon. Frequenters of the seashore may have noticed that this makes a difference of, say, a couple of feet as compared with moon at the quarter. On the 18th, then, wind and moon favored an exceptional high tide.

On Nov. 18 my barometer showed a sea-level reading of approximately 28.7 inches, perhaps, with one exception, the lowest I have ever happened to observe. When the barometer is low—that is, when the air pressure on top of the water is lessened—the water tends to rise. In support of this let me quote from William M. Davis's book 'Whirlwinds, Cyclones, and Tornadoes,' where he speaks of this phenomenon in the Bay of Bengal.

"The diminished atmospheric pressure about the storm centre allows the heavier surrounding air to lift the water, and for every inch that the mercury falls in the barometer the water will rise a foot, . . . and if a strong tide conspires with these other causes a great flood is produced."

The same rule that works in the Bay of Bengal works in New York Bay, I should think.

CHARLES VEZIN, Jr.

Yonkers, Nov. 22, 1918.

1918 Nov. 17
12.5h e.s.t. (−29)

44

The New York Times
Sat., Nov. 8, 1919
Page 5, Col. 1

HIGH TIDE FLOODS STREETS AT FERRIES

Unusual Rise Causes Delays on the Jersey Side for More Than Three Hours

UPPER PLATFORMS USED

Pilots Make Slips with Difficulty —Water Enters Cellars on New York Side

An extraordinarily high tide on the North River yesterday morning, said by the water front experts to have been caused by the northeast wind and the full moon, flooded the streets and cellars of the houses, interfered with the power plants of the Grand and Desbrosses Streets surface car lines, and partially tied up the Hudson River ferry services, which caused a good deal of inconvenience to the early morning commuters.

The passengers managed to board the ferryboats from the upper platforms on the Jersey shore, but the water was so deep in the streets below that trucks had to wait two hours before it subsided . . .

. . . The Brooklyn shore suffered, too, from the exceptionally high tide, and two men were marooned all Friday night on a jetty running from the Municipal Baths . . .

. . . The pilots on the Brooklyn ferryboats had considerable difficulty in making their slips on account of the tide, and many of the piers along the front were flooded. In Newtown Creek the water rose three feet in the early forenoon and flooded both shores. Pilots said these exceptionally high tides come about once every five years, and the exact cause has never been determined . . .

1919 Nov. 8
2h e.s.t. (+14)

45

Seattle Post-Intelligencer
Sun., Dec. 9, 1923
Page 16 HH, Col. 3

PACIFIC COUNTY IS HIT BY TIDE

SOUTH BEND, Dec. 8.—Pacific County is still estimating its losses and trying to repair them after the worst combination storm and tide the Willapa Harbor district has known for more than fifteen years . . .

. . . The long and narrow Willapa Bay acted as a gigantic funnel with the wind and tide pushing the water far above the scheduled 10.5 mark and inundating tidelands, the lower lying farms of the county and portions of South Bend and practically the entire city of Raymond . . .

1923 Dec. 7
6.5h P.s.t. (−23)

47

The San Francisco Examiner
Sun., Feb. 14, 1926
Page 1, Col. 4

COAST TIDES ATTACK FILM STARS' HOMES

Ventura Wharf Crumples Under Battering

Highways and Bridges Blocked; Long Beach Sea Wall Is Washed Out

LOS ANGELES, Feb. 13.—(AP)—Southern California was slowly emerging tonight from the three day raging of elements, in which gales and driving rains vied with almost unprecedented high tides, leaving in their converging wakes death, injury and property damage estimated in tens of thousands of dollars . . .

. . . mountainous seas, whipped into fury by off-shore gales, have resulted in three deaths by drowning, one injury and the destruction of one wharf, damage to numerous piers, beaching of many small fishing craft, and wholesale undermining of dwellings, cabins and strand walks on the water fronts . . .

. . . The loss of the Ventura wharf ties up shipping activity entirely at that city, all cargoes having been discharged on the one wharf. Six hundred feet of the structure collapsed . . .

. . . The Coast highway to San Diego was rendered impassable by washouts near San Juan Capistrano and farther south near Oceanside . . .

1926 Feb. 12
6.5h P.s.t. (−5)

48

The Boston Evening Globe
Thurs., March 3, 1927
Page 1, Col. 3

Wharves in Boston Under Water Foot Deep

. . . High, rough seas, whipped into fury by a heavy northeasterly gale, which at various places attained a velocity of 75 miles an hour, lashed practically the entire New England Coast line last night and this morning, compelling ships to seek shelter, and wharves to be submerged, and causing much damage . . .

. . . an exceptionally strong, high tide swept in at 10:46 this morning. The tide reached such a height that the water was on a level with the base of the caplogs of practically all the wharves along Atlantic av.

At Long Wharf, T. Wharf and several others the water seeped underneath the caplogs and the floorings, flooding the wharves with water that averaged about one foot deep . . .

Tide 13 Feet or Higher

Under normal conditions the tide today should have risen 11 feet at its highest, but the indications were that it went to the 13-foot mark or higher. Large, docked ships loomed high above the wharf structures . . .

1927 Mar. 3
21.5h e.s.t. (+15)

B–50

The New York Times
Sun., April 3, 1927
Page 19, Col. 2

Atlantic City Streets Flooded—

ATLANTIC CITY, N. J., April 2.—Driven up the beach and over the bulkheads by a fifty-mile northeaster, a heavy sea flooded parts of the Inlet section at high tide tonight.

Although the high seas did not reach the proportions of the February flood, water stood a foot deep in sections of Maine Avenue; waves lashed across the trolley tracks at the Inlet loop and gigantic combers washed over the bulkheads at the ocean ends of Vermont, Rhode Island and Gramercy Avenues . . .

1927 Apr. 1
20h e.s.t. (−6)

C–51

Every Evening
Wilmington, Del.
Tues., April 5, 1927
Page 3, Col. 4

LIGHTHOUSE KEEPER MAROONED BY WATER

. . . Due to the heavy tides caused by unsettled weather conditions of the past few weeks, the river embankment, 300 yards above the lighthouse, on the government reservation at the junction of the Delaware and Christiana rivers, suffered a break and the rush of water through the fissure virtually made the keeper, W. H. Johnson, a prisoner.

The water, at high tide, is two feet deep on the reservation . . .

1927 Apr. 1
20h e.s.t. (−6)

C–51

The New York Times
Fri., April 12, 1929
Page 5, Col. 2

HIGH TIDE CARRIES OFF A JERSEY BUNGALOW

. . . Although the southeasterly wind which prevailed most of the day showed a maximum velocity of twenty-four miles an hour in the city, it did considerable damage along the Jersey coast. Accompanied there by unusually high tides, it drove the sea waters inland for several hundred feet at some places. At Point Pleasant Coast Guards and volunteer workers put in a busy day trying to save bungalow colonies threatened by the rising waters. But despite their efforts one bungalow was carried out to sea, while five others were wallowing in shallow water close to shore and 600 feet of boardwalk was converted by the waves into driftwood. The damage there is estimated at $30,000 . . .

1929 Apr. 11
4h e.s.t. (+73)

53

The New York Times
Tues., Nov. 19, 1929
Page 20, Col. 3

13-FOOT TIDE SWEEPS BOSTON'S WATERFRONT

BOSTON, Mass., Nov. 18.—A record tide, driven four feet beyond its normal height by the easterly storm, inundated Boston's waterfront today, causing heavy damage.

The tide reached its highest point in many years with a rise of 13 feet 6 inches at 11:45 A. M. An unusual rise had been expected, but the water rose two feet beyond the mark predicted, flooding cellars and food stores piled up in wharf sheds.

The flood condition lasted for two hours, an hour before and an hour after the tide reached its peak. Half the length of Long Wharf from Atlantic Avenue was covered with seven inches of water . . .

. . . The Eastern Avenue approach to South Ferry was inundated with more than a foot of water and foot passengers unable to board the ferries were taken aboard on trucks.

Winthrop's seaside suffered much damage as the big waves battered the breakwater and crashed over the Shore Drive . . .

. . . The tide was the highest ever witnessed at the Boston airport, rolling up over the southern bulkhead and covering about a third of the runway . . .

1929 Nov. 17
22h e.s.t. (+54)

(*See also chapter 7.*)

54

The New York Times
Wed., Jan. 7, 1931 (Last Ed.)
Page BQ 27, Col. 8

Tides Cause Huge Damage

. . . Dense fog delayed vehicular traffic and harbor shipping and caused several mishaps in and near New York yesterday, while the highest tide in a score of years, stirred up by a full gale which battered the New England coast, caused extensive damage . . .

New England Coast Battered

. . . All along the New England coast the angry seas pounded wharfs, undermined cottages and flooded storehouses, The Associated Press reported. Occupants of offices along the Boston waterfront were forced to use ladders to get in and out of their places of business, while those using the harbor ferryboats were forced to use improvised gangplanks.

Several cottages were washed from their foundations at Hampton, N. H., where the tide was the highest known since 1909, and between thirty and forty Summer homes were surrounded by water . . .

. . . The streets of the Indian village of Taholah on the Quinault Reservation in Washington were flooded by the highest tide ever known there . . .

1931 Jan. 5
9h e.s.t. (+50)

56e

The New Haven Journal-Courier
Thurs., March 5, 1931
Sect. I, Page 2, Cols. 7, 8

REVERE HARD HIT BY EXTRA RISE OF TIDES

Many Homes Flooded, Forcing 200 Persons To Seek Shelter Elsewhere.

Revere, Mass., March 4(AP)—The Red Cross tonight came to the aid of civic authorities in supplying food and shelter to more than 300 persons left homeless by the battering of a storm tossed ocean.

With more than 75 cottages and homes flooded or demolished, scores of persons sought refuge from the city . . .

. . . About 25 pupils at the cities schools were forced to appeal to police when the unchecked tide inundated their homes or tore them to wreckage.

All police and fire reserves were called on duty and stationed at Revere Beach for the purpose of aiding sufferers and watching for further damage by the return tide. Police believed the midnight tide would be at least as severe as that of the day . . .

. . . Representatives Augustine Airola and Thomas F. Carroll told the governor the damage here was estimated at $1,000,000 and that greater loss was anticipated with the rising tide . . .

1931 Mar. 4
5.5h e.s.t. (−1)

(*See also chapter 7.*)

D–57

The New York Times
Fri., March 6, 1931
Page BQ 48, Col. 2

THIRD GREAT TIDE LASHES BAY STATE

BOSTON, March 5.—Towering seas continued to lash the coast of New England early today despite the fact that the wind and snow storm which accompanied yesterday's record-breaking tides had moved off-shore . . .

. . . The waves of the third consecutive abnormal tide, though somewhat abated, swept in at noon today and toppled several beach houses which had been weakened by the previous more savage onslaughts.

The loss is expected to run into the millions . . .

. . . The finale to the most destructive storm since 1898, today's tide ripped apart crumbling seawalls, again inundated several communities and tore more cottages from weakened foundations . . .

. . . great swells broke over seawalls an hour before high tide . . .

. . . Firemen started pumping out the inundated section of Beachmont, where water lay from three to seven feet deep, surrounding scores of houses. The nearest estimate of the loss is $3,000,000 . . .

. . . HALIFAX, N. S., March 5.—Damage estimated at a million dollars has been caused by the violent storm and record high tides along the coast of Nova Scotia during the last thirty hours . . .

. . . Wharves were carried away, at least one deep-sea cable twisted and torn, and bridges were smashed when a peaceful countryside received the worst battering by mountainous seas in the memory of its oldest inhabitants.

Devil's Island, standing like a sentinel off Halifax Harbor, where the snug homes of its fishermen nestle together, appeared to have borne the brunt of the attack. The tide was unusually high and as the spray, borne before the fierce wind, drove clean across the island, the women and children of the place fearfully watched the island men hauling their boats to safety.

Seas swept over the sheds housing the lifeboats, there being a life-saving station on the island, and for a time inhabitants of the island feared for their lives as the giant seas threatened to carry away the breakwater . . .

1931 Mar. 4
5.5h e.s.t. (−1)

D–57

The New Haven Journal-Courier
Fri., March 6, 1931
Page 20, Col. 1

EASTERN COAST STORM PASSES AFTER DAMAGE

Millions Of Harm Done By High Tides Sweeping Far Ashore Upon Towns.

Boston, March 5, (AP)—The storm which yesterday lashed the northeast coast, causing damage estimated in the millions, blew itself out today. There was no recurrence of the extreme high tide, which was responsible for the greater part of the destruction.

As the sea rolled back it left in its wake a shore line streamed with splintered dwellings and summer cottages and uprooted and undermined seawalls and breakwaters. Highways and roadbeds of electric and steam railroads were washed out in many places and road gangs labored to repair the damage. Although the force of the tidal storm was felt all along the North Atlantic states the most destructive blows fell on the Massachusetts and New Hampshire coasts.

Numerous summer cottages were demolished at Revere, popular greater Boston summer resorts, and at Hampton Beach, N. H.

Fear that today's tide would approach the record high of yesterday to multiply the damage already inflicted was found without foundation. The wind that had been blowing from the northeast, driving the sea upon the land, shifted to the northwest, serving to abate the heavy seas. Many sections that were flooded yesterday remained comparatively dry . . .

Revere Hard Hit

The Beachmont district of Revere, battered by three successive tides, tonight escaped further assault. The after midnight tide officials believed would be minus the fury of its predecessors which left the greater part of the district under water.

Acre upon acre of land on which homes or summer cottages rested were covered tonight with black placid water. The land being of the marsh variety failed to soak up the water . . .

Travel by Rafts

Those families who declined to leave their water surrounded homes were forced to go about on rafts or in row boats. The water in some areas reached a depth of six feet . . .

. . . At Highland Light, Mass., a shift in wind saved the Peaked Hills Coast Guard station and four cottages at Ballston Beach from tumbling into the sea. The beach was battered incessantly from Tuesday night until this noon when the change in wind was noted. The tide there was higher than anytime during the past ten years . . .

1931 Mar. 4
5.5h e.s.t. (−1)

D–57

The New York Times
Tues., March 10, 1931
Page 18, Cols. 1, 4

PORTLAND, Me., March 9 (AP).—A howling overnight southeaster, bringing heavy snow, sleet, rain and lightning, today had caused some damage along the Maine coast . . .

. . . An unusually high tide switched the mouth of the Goose Fair River, dividing line of Old Orchard and Saco, 100 feet to the south . . .

. . . NEW HAVEN, Conn., March 9.—Damage to the Connecticut shorefront from yesterday's storm will total $1,000,000, according to estimates compiled from reports received today. The shorefront suffered heavily from Greenwich to Madison. Record-breaking high tides were recorded over this area. In practically every colony cottages or bath houses were washed away and wreckage was strewn over lawns and roads . . .

. . . For the first time in recorded history the Housatonic River overflowed its banks . . .

. . . Beachfront communities in New York and New Jersey were busy repairing the damage done by the tides and gale over the week-end. On Fire Island bar, opposite Centre Moriches, the new inlet cut by the raging seas seemed to be filling in again . . .

(*See also chapter 7.*)

1931 Mar. 4
5.5h e.s.t. (−1)

D–57

The New York Times
Thurs., April 2, 1931
Page 2, Cols. 2, 3

HIGH TIDES MENACE NEW ENGLAND WITH A HEAVY GALE BLOWING

BOSTON, April 1.—April rode in to New England on the crest of a northeaster which tonight caused uneasiness along shore for fear of damage by high tides.

Three high tides are scheduled in eighteen hours. The first this noon ran a foot higher than the predicted stage, despite the fact that the wind was only just beginning to rise. As the day advanced the gale increased . . .

High Tides Wreck Summer Home at Southampton

. . . Blinding sheets of rain swept the streets of New York and its vicinity yesterday, while high tides and a strong northeast wind caused damage along the northeastern coast of the country . . .

. . . The Summer home of William F. Ladd, member of the New York Stock Exchange, at Southampton, L. I., was wrecked when a heavy sea undermined the house, which had been pounded by waves for several weeks.

. . . All along the Jersey coast bulkheads were battered and Summer homes damaged by the wind and tide . . .

. . . Trains on the North Shore division of the Long Island Railroad were held up for eighteen minutes by an open drawbridge at Main Street, Flushing, which had been opened to permit the passage of a tug and then could not be closed at once because of the wind and tide . . .

Tides Shatter Bulkheads.

LONG BRANCH, N. J., April 1 (AP).—Pounding waves, driven before a forty-five-mile northeast gale, shattered portions of bulkheads today between here and Highlands, threatening hundreds of cottages. A sudden shift of the wind to south before high tide, saved coast resorts from greater damage . . .

1931 Apr. 2
4h e.s.t. (−22)

E–58

The New Haven Journal-Courier
Thurs., Dec. 1, 1932
Page 7, Cols. 7, 8

Huge Tide In Boston Area Does Damage

Water Rushes Over Roads And Shore Towns Are Partly Submerged.

Boston, Nov. 30 (AP)—The highest tide of the season today swept over breakwaters and piers along the New England coast causing damage estimated at thousands of dollars. Scores of persons employed in Boston waterfront offices were marooned during the peak period of the tide and in Winthrop, flooded streets kept students in a school during the noon lunch period.

At Truro on Cape Cod and along the New Hampshire coast in the Hampton Beach area, damage to cottages was reported. The summer cottage of Osborne Ball of Boston at Truro tumbled into the sea when the thundering surf undermined the cliff on which it stood.

At high water time, about 12:30 p. m., the tide reached a height of 13.66 feet and unofficially was reported to have reached a height of more than 15 feet. The normal tide is 11 feet, four inches . . .

. . . In Boston the tide inundated the low lying piers of the Atlantic avenue section. The water seeped into the approaches at many of the famous old wharves, including Central, India, Long and T., and many trucks were stranded on piers. Ferry boat slips were flooded and many passengers were delayed for a short time until the water receded.

A sight that attracted much attention was that of ships lifted almost to street level by the rising waters. Meanwhile, crews worked vigorously to keep mooring ropes from snapping under the strain.

All along the north and south Massachusetts shores beach cottages were surrounded with water and in many instances serious damage was done to the structures by the beating of the surf.

For the first time since 1909, the town of Nahant was isolated when the waters of Lynn harbor inundated the narrow peninsula connecting the town with the mainland . . .

1932 Nov. 27
15h e.s.t. (−10)

60

The Oregon Daily Journal
Mon., Dec. 18, 1933
Page 1, Col. 2

Coast Area Pounded by Rains, Tides

Aberdeen, Dec. 18.—(AP)—While soggy skies continued to pour rain on this district, Grays Harbor attempted today to take stock of damage done by a great storm driven tide which flooded major portions of Aberdeen, Hoquiam and Cosmopolis Sunday.

A survey of the business district this morning indicated a loss in merchandise and fixtures of between $50,000 and $100,000. Flooded homes, street damage and road washouts will augment the total loss.

The port of Grays Harbor tidal gauge measured the rise at 15.8 feet, four feet above the predicted high tide mark and nearly a foot higher than any previous tide in history here . . .

. . . the chief cause was declared to be the great tide, supplemented by the 90-mile southwest gale . . .

. . . Eastbound traffic was threatened again this morning when another tide of over 11 feet began backing water over the lowland road between Aberdeen and Montesano. The series of 11-foot tides will continue until Thursday . . .

1933 Dec. 16
23.5h P.s.t. (+9)

63

The San Francisco Examiner
Wed., Aug. 22, 1934
Page 1, Col. 4

HUGE MYSTERY WAVES FLOOD L. A. BEACHES

Forty-foot Water Walls Strike; Two-Story Apartment Swept From Foundations; No Wind

NEWPORT BEACH, Aug. 21.—(AP)—A strangely acting Pacific Ocean, which has been running waves 30 and 40 feet high during the day, got out of bounds at high tide at 6:10 tonight and swept a two-story apartment building from its foundation and damaged other buildings. Part of the city was inundated a few feet . . .

. . . The waves threatened for a time to cut a new channel across from the ocean to Newport Bay, ripping out a large cut in the sand under the apartment building and across Central avenue . . .

. . . Portions of the Central avenue pavement, the only connecting link between the city and the fashionable residential section on Balboa Peninsula, were torn up, isolating for a time the residents on the peninsula . . .

. . . No wind was reported and no explanation for the unusual waves could be given by weather officials . . .

1934 Aug. 24
0h P.s.t. (−24)

64

The New York Times
Wed., July 17, 1935
Page 14 L+, Col. 7

Highest Seas in Years Threaten Oak Beach, L.I.

. . . OAK BEACH, L. I., July 16.—One of the highest seas in years, driven by a strong southeast wind for two days, pounded this village of twenty homes on the outer bar tonight, partly undermining the foundations of three cottages . . .

. . . After 10 P. M., when high tide had passed, the danger lessened. An automobile parking space on the beach was under more than a foot of water. The waves had dashed up within forty feet of the Coast Guard station here . . .

1935 July 16
23h e.s.t. (+46)

66

The Oregon Daily Journal
Wed., Jan. 4, 1939
Page 2, Cols. 3-6

. . . Aberdeen, Jan. 4.—(AP)—A sudden halt in the southwest gale and rain deluge which had hammered Grays Harbor for 48 hours until shortly before noon Tuesday temporarily ended a serious flood threat in Aberdeen and Hoquiam.

Water had backed up through sewers in parts of South Aberdeen and had just started over the Chehalis river dikes in two places, when the rain and wind halted and the high tide which had been pushed four feet above its predicted 10½ foot peak started to recede. Water had been backing into Hoquiam streets through sewers also . . .

Storm Floods Neskowin; Many Homes Damaged

Neskowin, Jan. 4.—A heavy sea following in the wake of a stormy night which saw the wind reach a 75-mile-an-hour velocity, flooded Neskowin Tuesday morning, causing an estimated damage to homes and buildings of from $50,000 to $75,000.

The turbulent sea water, which poured into the city between 9 and 11:30 a. m., wrecked the community kitchen, restaurant and warehouse and undermined the Neskowin store. Neskowin apartments and about 30 per cent of the homes were damaged . . .

1939 Jan. 5
20h P.s.t. (+14)

F–68

The Oregon Daily Journal
Thurs., Jan. 5, 1939
Page 1, Cols. 4, 7

. . . Four women were injured, one perhaps fatally, Thursday noon near Seaside as the northern Oregon coast suffered a recurrence of attacks by huge swells accompanying a high tide. The women were standing on a log when a swell picked it up and slammed it about . . .

. . . Marshfield, Jan. 5.—(AP)—A tide so high that many persons described it as a "tidal wave" moved houses, damaged small craft and destroyed cabins in the Coos Bay area Thursday.

Three houses were shifted on their foundations at Charleston and 15 cabins wrecked . . .

. . . High water forced the International Cedar Mill to shut down here . . .

1939 Jan. 5
20h P.s.t. (+14)

F–68

The Oregon Daily Journal
Fri., Jan. 6, 1939
Page 1, Col. 4

. . . Apprehension felt regarding another high tide along the coast today was allayed when the first community reporting, Nelscott, announced that the Lincoln county crest had passed shortly before 1 p. m. and that the extreme height of the tide was 12 feet, two feet lower than that of yesterday.

It is believed this relative figure will indicate the situation at other points, as the tide visitations yesterday were similar at all of them.

Tide gauge readings at Delake during the storm and high tides which ensued, were 15 feet Wednesday, when most damage was inflicted; 14 feet yesterday, and 12 feet today. A normal high tide reading of 9.8 had been scheduled for today.

Two lives are known to have been lost in the augmented tides which hammered the Oregon coast yesterday . . .

Resorts Flooded Again

Fog prevailed this morning at Astoria and south as far as Wheeler. Nelscott reported the sun shining. There was no wind at either point . . .

. . . Damage was less yesterday than during Tuesday's storm, the tide being as high, but not driven by a gale. The Tillamook beaches seemed to be harder hit yesterday, but resorts again were flooded as far south as Coos Bay . . .

The Oregon Daily Journal
Fri., Jan. 6, 1939
Page 1, Col. 7

Sea Unruly in California

Three Homes Washed Into Pacific; Others Damaged

Long Beach, Cal., Jan. 6—(AP)—Three modest beach homes in the Alamitos peninsula area southeast of Belmont shore were washed to sea today as giant breakers, riding in from the Pacific on high tide ground swells, crashed over the low sea wall . . .

. . . The tide also brought extensive damage to Manhattan and Hermosa beaches, where the highest water in years flowed as far as 180 feet inland.

But the Alamitos peninsula below Long Beach was hardest hit.

William E. Ross, boat builder there, said the tide was the worst in his 35 years' experience.

Mrs. D. H. Collins stood by and watched the tide carry her two-story dwelling into the Pacific . . .

. . . More than two feet of water roared in at some Santa Monica bay points, sweeping out the board walk along the strand between Manhattan and Hermosa beaches . . .

(*See also chapter 7.*)

1939 Jan. 5
20h P.s.t. (+14)

F–68

The New York Times
Mon., April 22, 1940
Page 1, Col. 2 (Late City Ed.)

GIANT WAVES LASH NORTHEAST COAST

Hundreds Marooned in Towns Near Boston—Blizzard Hits Maine and Vermont

BOSTON, April 21—Scores of persons were marooned today and the coast was hammered by mountainous waves whose spray washed over Minot's Light, 114 feet high, and lifted surf to a height of 130 feet at Deer Island, as a northeast storm, continuing from yesterday, brought to New England heavy rain, sleet, hail, snow and a gale blowing fifty-one miles an hour . . .

. . . A family of four and three other persons on Bassing's Island off Cohasset Harbor fled to the mainland in dories when the sea swept over the island for the first time since the storm of '98, in which the steamer Portland went down . . .

. . . The sea, lashed by the gale, surmounted seawalls, undermined streets and flooded cellars.

Hundreds of persons were temporarily marooned in churches in Winthrop and Beachmont by flooded streets, and services had to be called off tonight at one in Winthrop . . .

. . . Several hundred Summer homes at Hull were damaged by wind and sea. The tide late tonight was 11 feet 3 inches, six inches higher than the morning tide and the continuing gale increased the floods and coastal damage, driving waves and surf against cottages many yards from the ocean front . . .

1940 Apr. 21
7h e.s.t. (—34)

G–69

The New York Times
Mon., April 22, 1940
Page 34 L, Col. 1

Shirley Gut, formerly a strait between Winthrop and Deer Islands, but long since closed by storms, was nearly reopened by the sea, to the concern of army engineers who recently refused to let it be dredged out because anti-aircraft guns might have to be rushed to the island overland in event of war.

Tip of Maine Is Isolated

BOSTON, April 21—The northeast tip of Maine and its 7,000 residents were isolated tonight as a 50-mile-an-hour northeaster sent a high surf pounding against New England waterfront roads and property . . .

. . . An incoming tide, driven by the gale, flooded Quincy Shore Boulevard, main highway between Boston and Cape Cod, for three miles and halted automobile traffic.

Squantum, a Quincy peninsula of 1,500 residents and home of a Naval Reserve air base, was cut off temporarily as the tide swept across its only outgoing highway . . .

1940 Apr. 21
7h e.s.t. (—34)

G–69

The Oregon Daily Journal
Thurs., Dec. 26, 1940
Page 1, Col. 7 (Final Ed.)

High Tide, Wind Create Damage In Coast Region

. . . A nine-foot tide Wednesday, pushed by a 50-mile-an-hour wind, damaged seawalls and flooded Tillamook farms and the Coast highway.

Hammond, on the Columbia estuary below Astoria, reported today that the tide washed out the approach to the Hammond beach road Wednesday, but that there was no other damage . . .

1940 Dec. 26
17.5h P.s.t. (—87)

70

The Oregon Daily Journal
Fri., Dec. 27, 1940
Page 1, Cols. 1–4 (Final Ed.)

HIGH TIDES SPECTACULAR ON OREGON COAST

DELAKE, Dec. 27.—North Lincoln residents, under bright skies and a span of ocean rainbows, today estimated damage of a two-day Christmas beating by wind, rain and high tides.

Taft had the worst, with damage to the seawall that protects Pacific street along Siletz bay. Mountainous waves drenched that street, littered door yards, dug holes in lawns and removed 200 yards of filling back of the wall.

Nelscott reported damage to the seawall, removal of stairways to beach from Overlook property and piling of logs on the ramp . . .

Angry Seas Still Batter California

LOS ANGELES, Dec. 27.—(AP)—An angry ocean continued today to pummel portions of the California coastline, aiming its severest blows at the little town of Redondo Beach.

A house and a liquor store, normally, even at highest tide, 50 feet away from the water, were undermined in today's assault. Both collapsed.

Two houses which were dropped into the surf yesterday by the gnawing action of 25-foot combers and ground swells were being battered into debris today.

Damage estimates run as high as $250,000 . . .

1940 Dec. 26
17.5 P.s.t. (—87)

70

The Oregonian
Sun., Dec. 29, 1940
Page 6, Col. 2

Coast Awaits New Storms

. . . SAN FRANCISCO, Dec. 28 (AP)—The Pacific seaboard, battered by recent storms, braced itself for more onslaughts of wind and rain Saturday night, while high water flooded many roadways . . .

. . . Winter tides were at high peak. Salt water stood so deep on highway 101 south of San Rafael that many cars were stalled, and high-wheeled trucks were used to tow or push them to higher ground . . .

1940 Dec. 26
17.5 P.s.t. (−87)

70

The New York Times
Fri., Dec. 1, 1944
Page 25 L, Col. 1

HIGH WINDS, TIDES LASH THE CITY AREA

Third Wettest November Bows Out With Gusts Hitting 57 Miles and Snow Flurries

Commuters Delayed as Tracks, Ferry Slips and Roads Are Flooded—Planes Grounded

. . . The third wettest November on record blustered to a close amid snow flurries yesterday as winds reaching fifty-seven miles an hour swept the metropolitan area, disrupting railroad, ferry and air services. The tempestuous weather, the Weather Bureau predicted last night, would continue in strong to gale strength until some time today . . .

. . . The wind velocity started to increase about 9 A. M., when it was measured at 23 miles an hour, and ranged between 45 and 50 miles an hour in the afternoon, with gusts up to 57. It had subsided last night to 32 miles an hour and was expected to range about there throughout the night . . .

. . . The sea was whipped into almost record tides along New England's coast, causing damage estimated in the millions of dollars. Cape Cod bore the brunt of the storm. Coast Guardsmen evacuated persons on Nantucket Sound from Falmouth to Chatham, and dozens of homes that have withstood the September hurricane were wrecked. Provincetown reported eleven-foot tides inland, the worst in forty years. In New Bedford, floods crippled several industrial plants. In many coastal communities electric and telephone lines were down. Fishermen suffered large losses in gear.

Thousands of New York commuters were delayed in reaching work when high tides stranded them in Long Island and New Jersey. Long Island Railroad service was discontinued between 8:50 and 11:25 A. M. over Jamaica Bay between Hamilton and Howard Beaches when the tides covered the railroad trestle. Trains between Long Beach and Island Park were delayed.

The tide backing up into the Erie Railroad yard in Jersey City covered road approaches to the ferry line with three feet of water, and for the first time in eighteen years ferry service was suspended at 8:30 A. M., resuming at 10 o'clock. Water rose more than two feet above the ferry slips and flooded Pavonia Avenue, stalling many buses and trucks.

While the Central Railroad of New Jersey said that it had had no difficulty in loading its ferryboats, high tides north of Sea Bright overflowed tracks at several points, resulting in delayed service.

The high tide in Jamaica Bay cut off vehicular traffic on the Cross Bay Parkway and Rockaway Boulevard routes from the peninsula to the mainland, which were flooded from 8 A. M. until noon . . .

1944 Nov. 28
9.5h e.s.t. (−69)

71

The Daily Kennebec Journal
Augusta, Me.
Wed., Nov. 21, 1945
Page 1, Col. 8

Record Tide, 70 Mph Gale, Heavy Snow

Portland, Me., Nov. 20—(AP)—A fierce southeast gale whipped the Maine coast today causing waterfront damage running into hundreds of thousands of dollars.

. . . Sweeping up the coast, the gale, which recorded wind gusts of 70 miles an hour here, drenched southwestern Maine . . .

. . . In Machiasport, numerous sardine boats, hauled up for the winter, were set adrift by the high tide.

An estimated 28-foot tide at Eastport, on Passamaquoddy Bay, exceeded a previous high there of 27.1 feet, moving buildings from their foundations and wrecking wharves and waterfront bulkheads. Damage in Eastport alone was estimated unofficially at $100,000.

When the water flooded the Northern Herring Company wharf at Eastport, five women employes of the U. S. Customs and Immigration offices in a three-story wharf building were taken down ladders to safety.

Tidewaters of the Machias River washed out the Maine Central railroad tracks at four places between Machias and East Machias, interrupting travel from Bangor to Calais. Rails were torn up for a distance of 600 yards at one place. A paralleling highway was damaged but remained passable.

Reports of extensive damage to wharves, fishermen's "shops," and industrial plants came from Cutler, Camden, Bar Harbor and other "downeast" points . . .

1945 Nov. 19
3.5h e.s.t. (−13)

H–72

The San Francisco Examiner
Mon., Jan. 26, 1948
Page 1, Col. 7

Tides Flood Bay Area

S.F. BOY DROWNS; ROADS BLOCKED

An unprecedentedly high tide flooded portions of three Bay area counties yesterday and was blamed for the drowning of a San Francisco boy . . .

. . . Small craft warnings were hoisted on the Bay for northeasterly winds up to thirty-five miles per hour due this morning.

FLOODS ROADS—

The tide spilled onto several Marin County roads, including Highway No. 1 at Dolans Corner, south of Mill Valley, and a service road between San Quentin and San Rafael. Some autos stalled on the latter. The water almost overlapped Highway 101 just south of San Rafael.

In San Francisco, sewers backed up in the south of Market area, flooding several streets . . .

. . . The tide rise, six feet eight inches, was described by the Coast Guard as the highest due this year, although today's high tide, at 10:52 a. m., will reach six feet seven inches . . .

1948 Jan. 26
1h P.s.t. (+4)

74

The New York Times
Wed., Oct. 19, 1949
Page 59, Col. 1

Jersey Shore Streets Flooded

LONG BRANCH, N. J., Oct. 18 (AP)—Rising tides and high waves pounded beaches and flooded some streets in the shore area tonight.

Thirty-foot-high waves were reported at Seabright, where water inundated parts of Ocean Avenue six to eight inches deep.

Police said that not much damage was done but that Ocean Avenue was expected to be closed to traffic for about twenty-four hours.

1949 Oct. 21
13h e.s.t. (−6)

75

The Los Angeles Times
Thurs., July 19, 1951
Page 1, Col. 1 (Final Ed.)

Tide Floods Long Beach; Boat Saves 9

. . . Two expectant mothers and five children were among a number of persons evacuated by lifeguard boats from homes flooded by sea water at record high tide last night in the Long Beach Harbor area.

. . . A battery of pumps worked throughout the day yesterday to eliminate sea water which rushed into the area affected by the earth's subsidence.

More than 100 homes in a six-block-square area of the district were flooded following the third record high tide in three nights.

Tides of 7.2 feet swept through harbor area storm drain systems Tuesday night and sent water gushing through streets to flood small homes with as much as 14 inches of water . . .

. . . Some automobiles were left in the flooded streets and others were pushed or towed out of the path of the water.

Each day since Monday, residents said, the tides sent water into the area between Seaside Blvd. and Water St. . . .

. . . The piers at Berth 32 and Berth 33 on the harbor waterfront also were flooded by sea water during the high point of the tide.

The flooding is basically due to the land subsidence in the harbor area, although failure of some sandbag dikes and the plugging of pumps in the area also are blamed for the condition . . .

1951 July 18
1h P.s.t. (−20)

76

The Seattle Daily Times
Mon., Dec. 3, 1951
Page 16, Col. 6

New Storm Causes Flood Damage In North California

SAN FRANCISCO, Dec. 3.—(AP)—A new storm, on the heels of one which closed the Golden Gate Bridge Saturday for three hours, caused flood damage in Northern California today . . .

. . . Water stood three feet deep in sections of Sonoma, 35 miles north of San Francisco. A dozen ranches in Sonoma County were isolated. Eight schools were closed. Flood waters entered Burlingame, 15 miles south of San Francisco, and marooned people in stores . . .

1951 Nov. 29
11h P.s.t. (+36)

77

The Seattle Daily Times
Mon., Dec. 3, 1951
Page 13, Col. 2

Tide Spills Over Bank Of Duwamish

A high tide of 12.7 feet spilled over the west bank of the Duwamish River about 9 o'clock this forenoon. Water inundated lawns of three residences in Riverside Drive, a foot deep near Webster Street.

Occupants said little damage resulted, and the water receded by noon. Another 12.6-foot tide is due about the same time tomorrow . . .

1951 Nov. 29
11h P.s.t. (+36)

77

The San Francisco Chronicle
Sat., Dec. 29, 1951
Page 1, Cols. 7, 8 (Final Ed.)

Bay Area Gets a Soaking

High Tides Flood Marin; Valley Situation Eases

Except for the few dozen Bay Area families, whose homes have been flooded, this will be a wonderful week end to stay home.

The storm so far has been persistent, but relatively benign. Heavy rainfall has been general, but temperatures have been mild for this time of year, even in the mountains, and there have been no destructive winds.

High tides and a break in the dike north of San Rafael flooded Railroad avenue which leads to the San Francisco Bay Airport. The tide rose 6.9 feet above mean low tide.

The road to Mill Valley was under water at Dolan's Corners. So was Highway 101 south of Richardson's Bridge during the high tide.

1951 Dec. 28
9.5h P.s.t. (+11)

78

The New York Times
Fri., Oct. 23, 1953
Page 1, Cols. 1, 2 (Late Ed.)

Lower Manhattan Wetted by Tide As Full Moon Pays Us Close Call

Early commuters in downtown New York found the water curb-deep in a few spots off South and West Streets yesterday morning. A high perigee tide, possibly aided by the winds, had pushed sea water up into lower Manhattan storm sewers and out into the streets . . .

. . . A few cellars were flooded downtown and in coastal Brooklyn, and traffic was delayed by deep water in several New Jersey points. But there was no report of damage from the unusual tide . . .

. . . The high tide at 7:34 yesterday morning coincided with the full moon at 7:56 A. M. and came only a few hours after the moment when the moon was in perigee —its closest approach to the earth.

The moon travels an irregular path as it moves around the earth. At perigee, the closest point, when the moon's gravitational pull on the oceans exerts its greatest influence, the tides are high. The coincidence of perigee with the beginning of a full moon—the moment when the earth, the sun and the moon are in a straight line so both the sun's and the moon's gravitational pulls work together on the oceans—occurs twice each year, Joseph M. Chamberlain of the Hayden Planetarium explained . . .

. . . The Coast and Geodetic Survey which calculates for each day a tide forecast, had placed the tide yesterday morning at the Battery at 5.9 feet above the mean low water level, which is the "normal" low water level for the day. Low water yesterday was 0.8 feet below normal, so the range of the tide yesterday morning was 6.7 feet, a figure far above average, the agency reported . . .

1953 Oct. 21
21.5h e.s.t. (−21)

79

The New York Times
Sat., Oct. 24, 1953
Page 9, Cols. 5, 6

TIDE AGAIN SPILLS INTO CITY STREETS

Floods Caused by a Full Moon Close to Earth Disrupt Rail and Ferryboat Service

For the second day, a perigee spring tide caused tidal waters to overflow some city streets and low acres in the suburbs.

In addition to a few downtown Manhattan streets, the water affected areas along the New Jersey coast, both shores of Long Island and occasional points along the New England coastline as far as Eastport, Me.

A perigee spring tide occurs twice every year, when the full or new moon (a spring tide) happens to be nearest to the earth (the point of perigee). At this time both sun and moon simultaneously exert their strongest gravitational pull on the oceans. The full moon entered perigee on Thursday morning, while the semimonthly spring tide occurred yesterday.

The Army Corps of Engineers measured high tide at 8:22 A. M. yesterday off Fort Hamilton at the Narrows at 8.2 feet. This was 2 feet above average and one-half foot above high tide on Thursday morning.

Water Backs Up Drains

High water in the harbor backed up storm drains into Grand Street, West Broadway and West and Barclay Streets.

Between one and two feet of water lay in the cellars of 200 homes along Jamaica Bay in Hamilton Beach and Howard Beach in southern Queens. The Long Island Rail Road could not run trains to those stations until 10:20 A. M. because of flooded tracks.

The Long Beach Bridge to Island Park, L. I. was closed at 8 A. M. as Reynolds Channel overflowed the northern approach road . . .

. . . Ferryboats of the Erie Railroad floated so high above their slips in Jersey City, N. J. that no automobiles could board until 11:25 A. M. Commuters on foot, however, embarked by using upper ramps, while the rejected cars went to Manhattan by bridges and tunnels. High water also hampered commuters on the Lackawanna ferryboats and Hudson and Manhattan tube trains in Hoboken.

150 in Jersey Evacuated

The police and Coast Guardsmen evacuated a dozen residents and 150 employees of oyster-shucking sheds when the surf invaded Wildwood, N. J. Two schools in Union Beach, N. J., and one in Atlantic City were closed for part of yesterday by flood conditions. Five square blocks of Atlantic City were flooded by Absecon Inlet backing up in storm sewers and trolley service was disrupted there.

Artists living in converted sail-lofts on the Boston wharves had to evacuate yesterday morning with hip boots or in rowboats as salt water came over the sea wall. There were overflowing tides all along the Maine coast, but that is an old story there.

The United States Coast and Geodetic Survey predicted that the great tides would taper off today. This part of the coast was spared much damage, the oceanographers said, because we did not have strong east winds . . .

1953 Oct. 21
21.5h e.s.t. (−21)

79

The New York Times
Thurs., April 12, 1956
Page 63 L+, Col. 2

HIGH TIDES CAUSING FLOODS IN NORFOLK

NORFOLK, Va., April 11 (AP)—The highest tides in twenty years started flash floods in low-lying Hampton Roads areas tonight and isolated two communities.

The rising water halted ferry service across Hampton Roads, blocked highways, forced closing of the James River Bridge at Newport News and seriously interfered with coastal shipping.

The towns of Poquoson and Willoughby were cut off.

The Army dispatched a fleet of amphibious vehicles from Fort Eustis on an emergency mission to restore communications with them.

The floods were precipitated by strong northeast winds that raged up to seventy miles per hour in gusts . . .

1956 Apr. 13
7.5h e.s.t. (+115)

80 *(Alternate)*

The Los Angeles Times
Tues., Feb. 4, 1958
Part 1, Page 1, Col. 3

Tide, Surf Hit San Diego Bay Community

By a Times Correspondent

IMPERIAL BEACH, Feb. 3—High tides and pounding surf smashed at homes and the boardwalk at the height of today's storm, creating an emergency condition that led to proclamation by Gov. Knight of a state of disaster in this South San Diego Bay community.

At least four families were prepared to evacuate their ocean-front homes. One was partly undermined as the boardwalk in front collapsed.

City crews rushed truck-loads of rock and sand to the beach front in an effort to protect property.

Mayor Cecil Gunthorp telegraphed Gov. Knight that "the City Council has declared a local emergency, wherein all cash reserves have been used and financial assistance is needed."

Under Knight's proclamation, the State will provide aid . . .

1958 Feb. 4
19.5 P.s.t. (+39)

81

The Boston Herald
Wed., April 2, 1958
Page 1, Cols. 6–8 (Late City Ed.)

Giant Waves, 82-mph Waves Lash Coast, Cape

A roaring northeast storm at sea sent winds up to 82 miles an hour through Nantucket last night and pounded waves against the Winthrop sea wall that towered 50 to 75 feet into the air.

Low roads in several coastal communities between Chatham and Portsmouth, N. H., were flooded, but damage was less than feared.

Revere street in Winthrop and Wessagussett road in Weymouth were among inundated thoroughfares between 8 and 10 p.m. when the seasonably high tides were pushed three feet higher by the storm.

Water on T Wharf

During the storm evening tides in Boston ran several feet higher than normal. More than 50 residents of apartments on T Wharf were marooned when the tides swept over wharf stringers.

Fishing boats tied up to the wharf, and at adjacent wharfs were at doorstep level while the tides were high.

A number of automobiles parked on the wharf were also marooned by the exceptionally high tides and some of them had their electrical systems soaked as high winds swept the water across the wharf planking . . .

1958 Apr. 3
19h e.s.t. (—8)

82

The Los Angeles Times
Wed., Feb. 5, 1958
Part 1, Page 2, Cols. 4, 5

High Tides Batter at Southland Coast Areas

High tides, lashed by the same Pacific storm that brought heavy rains to the Southland, battered at Southern California coasts yesterday.

At Oxnard Beach, northwest of Port Hueneme, Navy helicopter and crash-boat crews reported they failed to find the body of a 17-year-old Santa Paula girl who was washed into the sea late Monday. The teen-ager, Judith Lou Nasalroad, was caught by a huge wave while walking on the beach. The tumbling waves swept her into the sea.

On the Alamitos Bay Peninsula near Long Beach, two feet of salt water damaged lawns from 56th to 59th Place along the bayfront. Crews blocked off Ocean Blvd. at 50th Place after a high tide pushed water over a 30-inch cement seawall.

A U.S. Coast and Geodetic Survey team said a 7.1-foot peak tide at 9:50 a.m. caused the flooding. City crews piled sandbags atop the seawall in preparation for a similar tide peak this morning.

In Seal Beach, bulldozers piled up an 8-foot sand dike along Seal Way east of Municipal Pier to guard a row of apartment houses.

In San Diego County, work crews labored in a rainstorm to pile rocks along a section of Imperial Beach waterfront where four homes were undermined by high tides Monday. Gov. Knight declared the beach front a disaster area to make State funds available to work crews . . .

1958 Feb. 4
19.5h P.s.t. (+39)

81

The Boston Herald
Thurs., April 3, 1958
Page 1, Col. 3 (Late City Ed.)

2 Big Tides Rip Walls Main Roads

The 18th northeast storm since December kept hammering at New England last night, causing coastal damage from tides four feet above normal that marooned communities and smashed waterfront property twice in one day.

Again at 9 o'clock last night high tides thrashed exposed locations, casting up more sand, rock, sections of cottages, fishing and lobster gear and other debris. The unusually high morning tide was whipped by 70-mile-an-hour winds.

Nahant Isolated

Nahant again was isolated as Lynn Shore Drive, leading to this town from Lynn and the only means of getting to Nahant, was under three feet of water for a second time at 9 p.m.

Nearly 100 families were marooned in their homes on Surfside and Beach roads in Lynn by last night's high tide.

Water again was licking the sides of the Metropolitan Police station and the amusement stands on Revere Beach Boulevard, which was closed to traffic, and was gushing downward into Ocean avenue, in the rear of the beach area.

Winthrop Shore drive was closed and 400 families in the Point Shirley section of Winthrop were marooned, as were many more in the Beachmont area of Revere . . .

1958 Apr. 3
19h e.s.t. (−8)

82

The New York Times
Wed., Dec. 30, 1959
Page 6, Col. 4

NEW ENGLAND HIT BY SAVAGE STORM

Near-Record Tides Strand Scores

BOSTON, Dec. 29 (UPI)—A savage storm swept into New England from the Midwest today. Carrying snow, sleet and rain, it churned up the highest tides in 108 years and stranded hundreds of persons.

Boston harbor's tide rose about two and a half feet above normal. Wind-lashed breakers surged over beaches and seawalls on the highest tide since 1851 when an April storm carried away a stone lighthouse.

The unofficial reading by the Coast and Geodetic Survey was 14.3 feet above mean low tide as compared with the 108-year-old record of fifteen feet.

Huge seas, born of gale-lashed winds, pounded the coast and inundated low seaside areas. Roads and cellars were flooded. Two bridges in Maine were awash and telephone and power lines were knocked out.

Boats Rescue 300

Three Coast Guard boats rescued 300 men, women and children from flooded homes in Hull on Massachusetts' south shore.

The sea surged over two bridges at Kennebunkport, Me., marooning some eighty families. Two feet of water covered the bridges but officials said the families were in no danger.

1959 Dec. 29
5h e.s.t. (−18)

(*See also chapter* 7.)

I–83e

The New York Times
Wed., Mar. 7, 1962
Page 1, Cols. 2, 3 (Late City Ed.)

Snow, Rain, Gales, Tides Lash Mid-Atlantic States

A savage storm lashed the mid-Atlantic states with snow, rain, gales and high tides yesterday from Virginia into New England. At least nine persons were killed and six were missing last night.

Flooding forced thousands of persons out of their homes and electricity was cut off from 85,000 users. The damage in the Atlantic City area alone was estimated at more than $1,000,000 . . .

. . . winds up to sixty miles an hour roared in between 2 P. M. and 2:50 P. M.

The Weather Bureau warned that high winds would continue today, bringing tides three to five feet above normal and causing new flooding of low-lying areas.

Railroad and ferry travel was hampered in New Jersey and Long Island. A Hudson and Manhattan Railroad train with 494 passengers, many of them standing, was stalled for more than three hours at Kearny, N. J., by the flooding of the Passaic River . . .

1962 Mar. 6
4.5h e.s.t. (−31 min.)

J–85

(*See also chapter* 7.)

The Los Angeles Times
Fri., March 6, 1970
Page 10, Cols. 1, 2

WINDS, HIGH TIDES

Two Beach Areas Pounded by Surf

Two sections of the Orange County coastline suffered heavy damage Thursday morning from a combined attack by high tides and storm winds.

Seawalls valued at more than $75,000 were battered down by waves which then chewed at the foundations of several luxury homes on the shores of Capistrano Beach.

At Newport Beach, heavy surf again took a mile-long bite of sand from an area of which the pier is the center, and threatened to undermine lifeguard headquarters at the foot of the pier . . .

. . . High tide, cresting at 6.3 feet just before 8 a.m. Thursday, was pushed by westerly winds of 25 to 30 m.p.h. Heavy surf at Capistrano Beach pounded against several hundred feet of wooden seawall protecting homes on Beach Road and smashed it into splinters.

Breakers then chopped away beach sand and sloshed against the foundations of several residences . . .

. . . Anticipating another high tide of about 6.4 feet this morning, residents ordered an emergency haul of rocks and boulders to replace the seawall.

Orange County Weather Central said, however, Thursday's strong winds should be diminished by today . . .

1970 Mar. 6
18h P.s.t. (−32)

92

The Virginian-Pilot
Norfolk, Va.
Sat., March 27, 1971
Page 1, Cols. 2–4

. . . The season-mocking snowstorm which ushered in the sixth day of spring for much of the Atlantic Seaboard pushed tides above normal and plunged thermometers below average Friday.

Tides crested at Sewells Point at 9 p.m. at 6 feet, 2.8 feet above normal and the highest since the Ash Wednesday storm of 1962, the weatherman said.

High tide at Virginia Beach measured 7.6 feet, or 4 feet above normal.

Willoughby and Ocean View appeared hardest hit by the wind-driven tides, although scattered flooding was reported throughout the area from Colonial Place in Norfolk to Wolfsnare Plantation in Virginia Beach.

Water was knee-deep in the parking lot of the Quality Court Motel at Willoughby Spit. The wooden pier at Virginia Beach reportedly suffered damage . . .

. . . Norfolk police said the worst flooding Friday occurred at Ocean View, on Mayflower Road in Colonial Place, Olney Road, West Main Street, Boush Street, and Mowbray Arch. The 7900 block of Hampton Boulevard was impassable for a time because of high water, police reported . . .

1971 Mar. 26
9h e.s.t. (—10)

L-93e

Maine Sunday Telegram
Portland, Me.—Final Ed.
Sun., Feb. 20, 1972
Page 1, Col. 3

. . . A wild northeast blizzard, with snow taking a back seat to high tides and winds, wreaked havoc on southern Maine coastal towns before spreading slowly across the rest of the state . . .

. . . The famed pier at Old Orchard Beach, for example, gave way before the rolling sea. The large arcade section at the end of the pier was torn away and the wreckage washed up on the beach.

In Kennebunk, selectmen will seek state aid for what they describe as a disaster area.

About 30 families were evacuated along Kennebunk Beach and in the Great Hill section near the beach. Severe flooding washed out roads, and high seas crushed a portion of the granite and wood sea wall along the Kennebunk beaches.

A couple was rescued from their Kennebunk Beach home after surf began pouring through the front windows . . .

1972 Feb. 16
4.5h e.s.t. (+67)

96

The Oregonian
Wed., Dec. 12, 1973
Page 24, 3M, Cols. 4, 5

Tidewaters flood Washington towns; winds to ease off

Strong coastal winds Tuesday blew water from a near-record 16-foot tide over the seawall at Tokeland, Wash., leaving water a foot deep throughout town.

Flooding caused by the tide and winds also was reported at nearby Raymond and South Bend. Police said water reached depths of four feet in the streets of the two communities. No injuries were reported.

The touchy period came between 2 and 3 p.m. at the peak of the high tide when winds of 75 miles per hour were reported at Seaside.

The wind-caused flooding at Tokeland pushed a large trailer house out into a street and washed another house off its foundation.

Waves breaking over the seawall near the general store and post office threw logs against the store and littered the road with rocks, driftwood and debris.

1973 Dec. 10
4.5h P.s.t. (+21)

M-98w

The Los Angeles Times
Wed., Jan. 9, 1974 (CC Ed.)
Part I, Page 1, Cols. 2, 3

Giant Waves Pound Southland Coast, Undermine Beach Homes

Sandbag Barriers Erected to Ward Off Tidal Assault.

Giant wind-driven waves riding on surging high tides battered the Southern California coast Tuesday, damaging homes and flooding nearby areas.

Occupants of many beachfront homes from Santa Barbara to San Clemente erected sandbag barriers throughout the day in preparation for the next high tide at 10:08 a.m. today.

The wave and tidal assault came as rainfall from a five-day storm tapered off after dropping 7.69 inches in the Los Angeles Civic Center.

In Orange County, supervisors proclaimed a "local emergency" for wave-battered coastline sections.

(*See also chapter* 7.)

1974 Jan. 8
4h P.s.t. (—2)

N-99

The Los Angeles Times Fri., April 23, 1971 Part 1, Page 3, Cols. 1, 2

Heavy Surf, Tides and Winds Batter Oxnard Shores Homes

A combination of unusually high tides, heavy surf and strong winds Thursday caused considerable damage to six expensive homes along a three block stretch of Mandalay Beach Road at Oxnard Shores, north of Oxnard Beach.

According to officials, the crescent-shaped beach area, which is annually pounded by the wind and sea, has been under its latest, and perhaps greatest, onslaught for several days.

Thursday, a section of beach 60 feet wide and 12 feet deep disappeared into the ocean.

The damage left the six homes, valued at between $60,000 and $80,000, either hanging over a weak, sandy cliff or stranded on pilings that have "only 5 feet of sand to go before there's nothing to hold them up," Police Capt. Jack Snyder said . . .

1971 Apr. 24
3h P.s.t. (—34)

94

Chapter 2.

The Impact of Perigean Spring Tides Upon Representative Events in American Nautical History

Without pragmatically asserting a total and absolute causality of relationships in any of the following circumstances, there is, nevertheless, ample justification for the fact that, on certain occasions, perigean spring tides have played a significant role in determining or altering the course of nautical history. A few episodes researched from American naval annals will serve to indicate the strategic importance of these tides. Since the increases in amplitude [a] associated with these tides (and winds) may occur in rather widely varying degree, the influences of such amplitude variations can be either detrimental or desirable.

Perigean Spring Tides as an Aid to Navigation

Numerous cases have been mentioned in the preceding chapter in which destructive coastal flooding resulted from perigean spring tides that occurred in conjunction with strong onshore winds. Additional instances also can be cited in which moderate but navigationally important increments in tidal heights have had a direct impact upon historical events. These lesser increments were provided by perigean spring tides reinforced by light but steady onshore winds, generally insufficient to cause flooding. Appropriate examples are given below.

[a] The term "amplitude" is sometimes used in this volume in a general physical sense to designate the magnitude of either a positive or negative displacement of the tide with respect to mean water level, in preference to the more restrictive words "rise" or "fall" of the tides. The expression "increased amplitude" collectively allows for the algebraic increment in *both* the high and low waters associated with perigean spring tides.

Strictly defined in tidal nomenclature, the value of the amplitude is equivalent to one-half the range (see fig. 6 in appendix), and may differ quantitatively from either the rise or fall (the vertical displacement of the surface of the sea respectively above or below the local chart datum) at times of high or low water. The word amplitude is also used as a mathematical coefficient (i.e., "amplitude of a constituent") in the harmonic analysis of tides.

The quantitative information provided by accompanying eyewitness accounts, when coupled with supporting data from modern tide tables, point realistically to the fact that occurrences of this particular type involving perigean spring tides do not necessarily require the alignment of perigee and syzygy within the close limits of agreement in time possessed by the cases of severe coastal flooding previously described.

The Fate of the Frigate *Trumbull*

At the outset of the Revolutionary War, the American colonies had no organized navy, and much of the burden of the war effort was borne by privateers and by ships provided by the individual new States. However, limited funds were shortly authorized by the Continental Congress for the establishment of a small complement of Federal Navy vessels, and existing shipyards along the coast were given the task of constructing these new ships of war.

Early in the year 1776, at the Connecticut River (Brainerd Quarry) shipyard of John Cotton in East Middletown, Chatham Township (then consisting of several parishes ranging from present-day Portland to East Hampton), work was started on the frigate *Trumbull* of 28 guns. Lofting was begun near the end of February [1] and the ship was launched on September 5.[2] The ensuing activity can only be described as involving the ultimate in misplanning as well as a classic blunder in shipbuilding.

In the lack of present-day information concerning the exact outboard profile of this ship, the body plans used in construction of the *Trumbull* can only be assumed to be those specified for the official design of a Continental frigate.[3] If this conjecture is correct, the *Trumbull* had a full-load draft of 18 ft 4 in. which, allowing for an additional navigational safety factor of 2–3 ft of keel clearance, was still in excess of the minimum water depth at the mouth of the Connecticut River at any ordinary high tide. The *Trumbull* ran aground on a bar.[b]

The original of the accompanying early chart of the mouth of the Connecticut River (fig. 4), titled "Captain Parker's Chart of Saybrook Barr" [sic], with engraving done by Abel Buell, Connecticut's first engraver, is in the possession of the Connecticut Historical Society. A heliotype copy made from a very exact tracing of the fragile chart (from which published version fig. 4 was reproduced) occurs in "The Public Records of the Colony of Connecticut, May 1768–May 1772." [4]

The date printed on Captain Abner Parker's chart is 1771. However, information provided by the Connecticut Historical Society and published in a professional paper of the society [5] dealing with this early chartmaker reveals that the Governor's House shown on the chart was not actually built until 1784. Accordingly, the chart must have been several times revised and updated from its original publication date, which the Connecticut Historical Society states could not have been earlier than 1784.[6]

A further search reveals that no earlier British or American chart exists in the Geography and Map Division of the Library of Congress, and even the contemporary *Atlantic Neptune* charts do not extend west of Newport, R.I., in this section of Long Island Sound.

With these explanatory comments, it may safely be assumed that Abner Parker's chart provides an accurate and at least very representative contemporary indication of water depths in the vicinity of Saybrook Bar during the period under discussion. On this chart, the shallowest water depth in the principal navigation channel at the mouth of the Connecticut River is given as 6–8 ft, with that over the closely adjoining bars being only 4–7 ft.

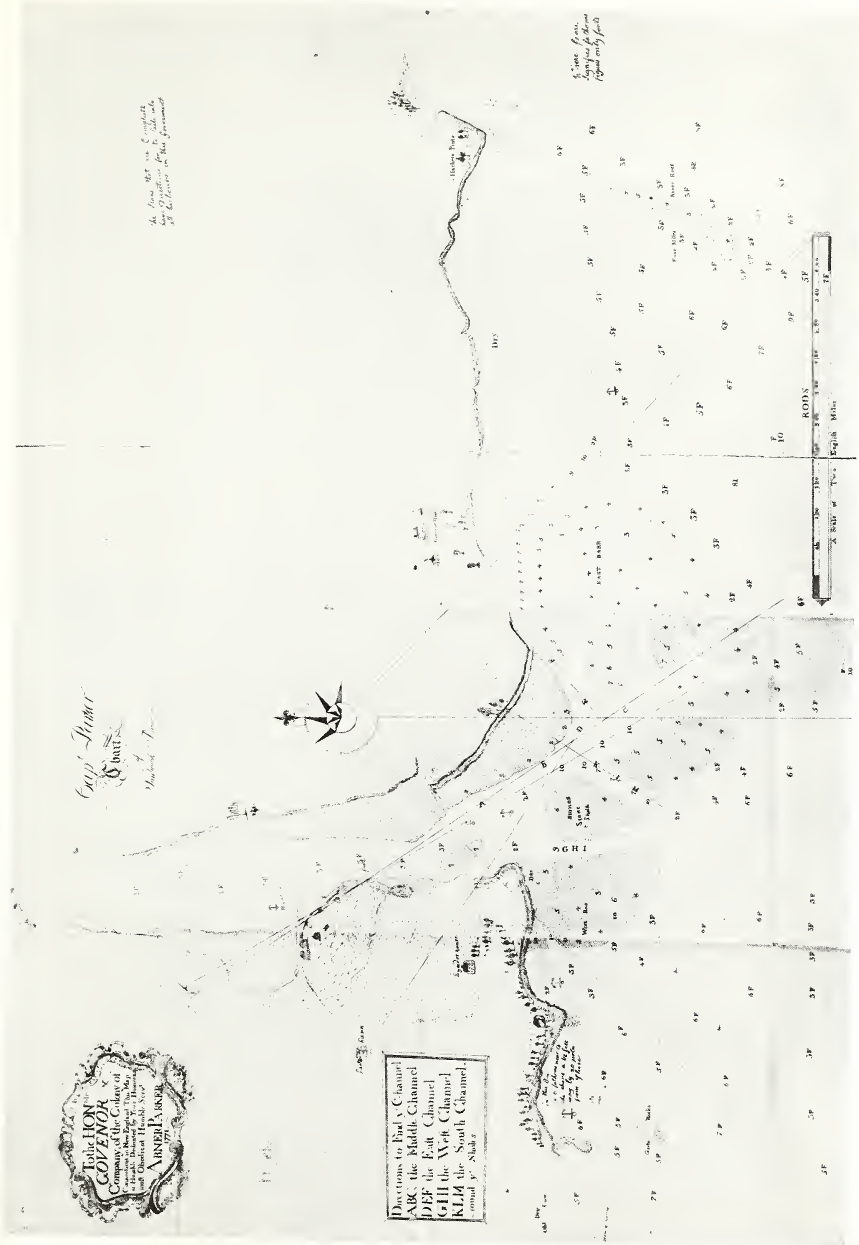
The earliest available nautical chart (fig. 5) for which detailed hydrographic soundings were made of this river mouth and its associated bars by the Coast Survey (the forerunner of the present National Ocean Survey) is chart No. 360 (1st edition) of the Connecticut River, published in 1853. Soundings on this chart (figs. 6–7) clearly show that the least depth of water anywhere directly along the designated ship channel or over immediately adjacent bars is 5½–7 ft, which is quite similar to that shown on Captain Parker's chart 79 years later. On the Coast Survey chart, the height of mean low water above the chart plane of reference is 0.6 ft, and the rise of highest tide observed above this plane of reference up until the publication date of the chart is given as 5.4 ft. From modern data, the mean range of ordinary spring tides at Saybrook Jetty at the mouth of the Connecticut River is 4.2 ft, and that at Old Saybrook Point is 3.8 ft.

With consideration to the preceding ship-draft and hydrographic sounding figures, together with others to be discussed later in this same section, the *Trumbull* obviously could not get off the rivermouth bar on which she had grounded at any ordinary high waters (including spring tides). As a result, she was prevented from taking any part in naval actions throughout the entire early portion of the Revolutionary War.

Although those involved were repeatedly prodded by admonishments from militarily interested parties in Congress [7] and in Connecticut,[8] including an appeal to president-to-be John Adams (at that time delegate to the Continental Congress from Massachusetts and member of the Board of War), all efforts to get the *Trumbull* off the bar were without success. An indication of the existing state of despair and of the fact that the shoalness of the water constituted the principal problem to be overcome showed in this same letter from William Vernon to John Adams, dated December 17, 1778. The letter quoted the opinion of a New England mariner aspiring to command the new frigate, one Captain Hinman. This authority claimed that only by the use of a "camel" (the name given to a type of special flotation gear) was there apparently any hope of clearing the bar.[9] With the *Trumbull* a firm captive within the Connecticut River, the vessel was in danger of "sitting out" the entire Revolutionary War.

On August 11, 1779, an unusually high water occurred associated with a perigean spring tide. The tide was produced by a close alignment (difference, −20 hours) between perigee and syzygy, with the mean incidence of the two phenomena taking place at approximately 7:00 a.m., 75° W.-meridian time, on that date. The resulting perigean spring tide could, of course, have been enhanced by sustained, strong, onshore winds. Although contemporary weather records from this immediate vicinity are lacking, a diary account of local weather conditions at New Haven, Conn., during the Revolutionary War period, preserved in the vault of the National Climatic Center, NOAA, indicates that the wind conditions were calm there on this date in 1779. This would tend to indicate the presence of high atmospheric pressure over the area. Similar contemporary records show that no strong hydrological runoff from recent severe rainfall, or melting snow or ice, occurred to swell the height of the waters at the river mouth.

[b] Considerable confusion seems to exist in modern reference sources concerning whether the *Trumbull* actually grounded or was simply blocked by the rivermouth bar; however, compare the direct contemporary quotations in references 14 and 16 which follow.



Courtesy of Library of Congress and the Connecticut Historical Society

FIGURE 4.—Captain Abner Parker's chart of Saybrook Barr [sic] at the mouth of the Connecticut River, engraved by Abel Buell and dated 1771, but probably revised to at least 1784 (see text).

Existing historical accounts [10] reveal that, precisely on this day of welling perigean spring tides, the *Trumbull* cleared the bar. In view of Captain Hinman's earlier statement, it is quite probable, although only permissible by inference—lacking any detailed account of the actual floating-out procedure—that the process of clearing the bar was aided by supplementary flotation gear. Of greater certainty, with consideration to the exact agreement between the dates of ship flotation and perigee-syzygy, is the fact that the sensible increase in tide height produced by this very close alignment between perigee and syzygy was a definite contributing factor in release of the ship.

Due care must be exercised in substantiating this assertion. Conceding, from the quantitative evidence later to be presented, that *ordinary* spring tides were not adequate to this purpose (very nearly 60 cases of ordinary spring tides having occurred during the total of 1,071 days since ship launching) it must fairly be noted that, in the cycle of astronomical events, 13 cases of perigean spring tides also had been passed over during that same 3-year period. This circumstance requires further evaluation.

Following the ship's original September 5, 1776 launching date, completion of the rigging and top hamper would undoubtedly have taken some months, and considerable additional fitting time would have been required before the vessel was ready to proceed to New London for loading of stores. The continuous slippage of ship-readiness dates through delays caused by such factors as nonavailability of spars, desertions among the ship's crew, change of command, etc., indicated in the documents quoted below, can readily account for the fact that possible other opportunities offered by any of these 13 previous perigean spring tides for a tide-assisted escape from the sandbar were not used.

Also at issue is the exact date on which the *Trumbull* first made the trip from Chatham down the Connecticut River and ran aground on a sandbar at the mouth. Although no discoverable record covering this precise episode exists, experts on Connecticut's history seem to feel that, because of the pressing need for the frigate's services, the journey down river and the subsequent stranding occurred during the late autumn of this same year.[11] Of considerable significance in this connection is the earliest date on which river ice might interfere with the vessel's passage downstream. Years of climatological records show that at least the upper reaches of the Connecticut River are customarily frozen over during some portions of, and occasionally most of the time between, November and March.

A book titled *The Record of Connecticut Men in the Military and Naval Service During the War of the Revolution, 1775–1783* gives both support as well as several clues to this supposition that the *Trumbull's* stranding and resulting shore problems with, and desertions by, the ship's crew lasted from the latter portions of the year 1776 to the early portion of 1779:

". . . Of 109 officers and crew variously assigned to the *Trumbull* between Sept. 15, 1776 and Jan. 22, 1778, some 35 deserted, 'run' or left the ship without liberty mostly in July 1777, but some in Aug. 1777 and lasting until Feb. 9, 1778. . ." [12]

". . . Its first Captain, Dudley Saltonstall, being transferred to the *Warren*, Capt., J. Nicholson of Penn., took command in latter part of 1779. . ." [13]

One official mention of the *Trumbull's* stranding, and the activities of the British fleet in the area, occurs in the *Colonial Records of Connecticut:*

". . . During 1778, Deshon of the Boston [Navy] Board spent much time in Conn. attending to the naval business of that state. This had to do chiefly with freeing the *Trumbull* frigate from a sandbar upon which she had grounded. During the same year Vernon was for a time at Providence endeavoring to get to sea the Continental vessels which the British had blockaded in that port. . ." [14]

Various resolutions passed by the Council of Safety or the Board of War during the period 1778–1779 also provide a chronological account of certain postlaunching activities in connection with the frigate *Trumbull* and indicate that, as of January 1778, the *Trumbull* had not yet been outfitted with spars:

"At a Meeting of the Governor and Council of Safety Holden at Hartford in and for the State of Conn. on the 29th day of Jan. A. D. 1778. *Voted*—That an order be drawn on the committee of Pay-Table to draw an order on the Treasurer for the sum of £250, in favour of Capt. John Cotton . . . for procuring spars for the use of this State to be in account.

Ordered delivered Jan. 29, 1778." [15]

Same . . . "on the 25th Day of Feb. 1778.

"Whereas the Hon^{ble} Congress of the United States have authorized and requested his Excellency the Governor and this Board to cause the continental frigate *Trumbull,* now lying near the mouth of the river Connecticut and there detained by reason of an apprehended difficulty of getting over a bar of sand, call'd Say Brook Bar, to be removed and got over said bar ready to proceed to sea &c. Therefore,

"Resolved and ordered by his Excellency the Governor and this Board, That Capt. John Cotton of Middletown

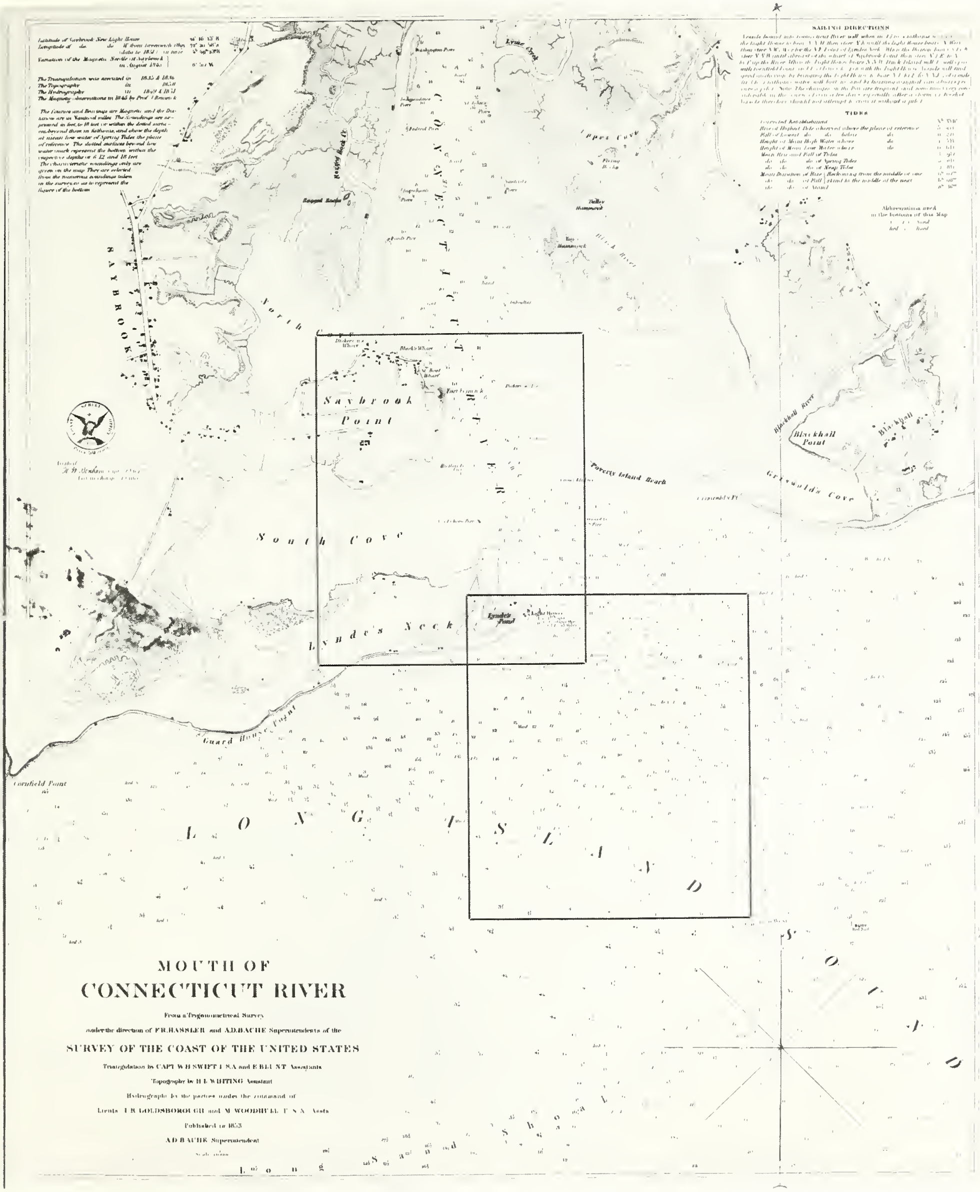


FIGURE 5.—U.S. Coast Survey Chart No. 360 (1st ed.) of the mouth of the Connecticut River, published in 1853, including basic tidal data. Boxed areas are enlarged in figs. 6 and 7.

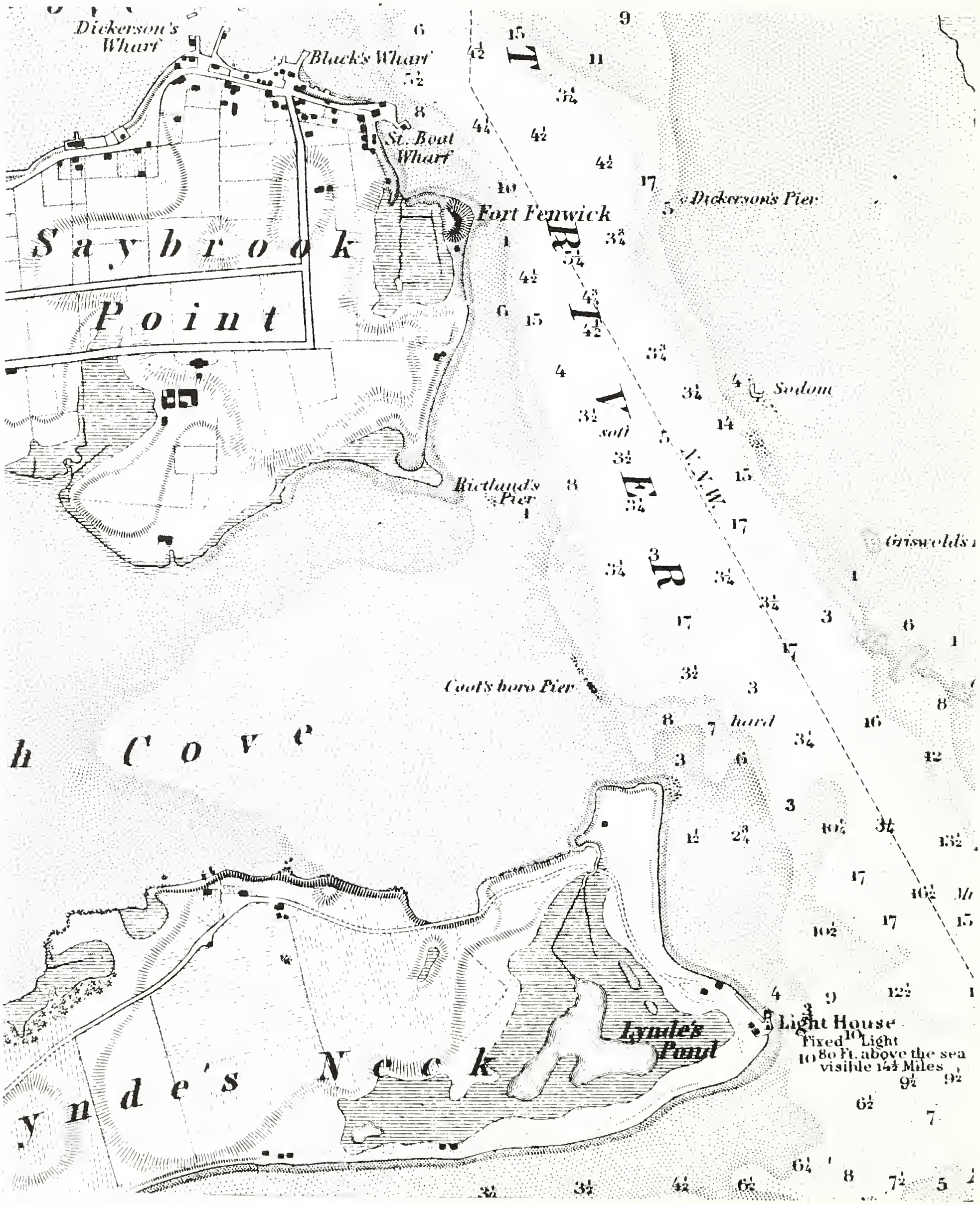


FIGURE 6.—Enlarged section of the U.S. Coast Survey Chart No. 360 (1st ed.), showing soundings at the mouth of the Connecticut River between Fort Fenwick and Lynde's Point made in 1849 and 1851.

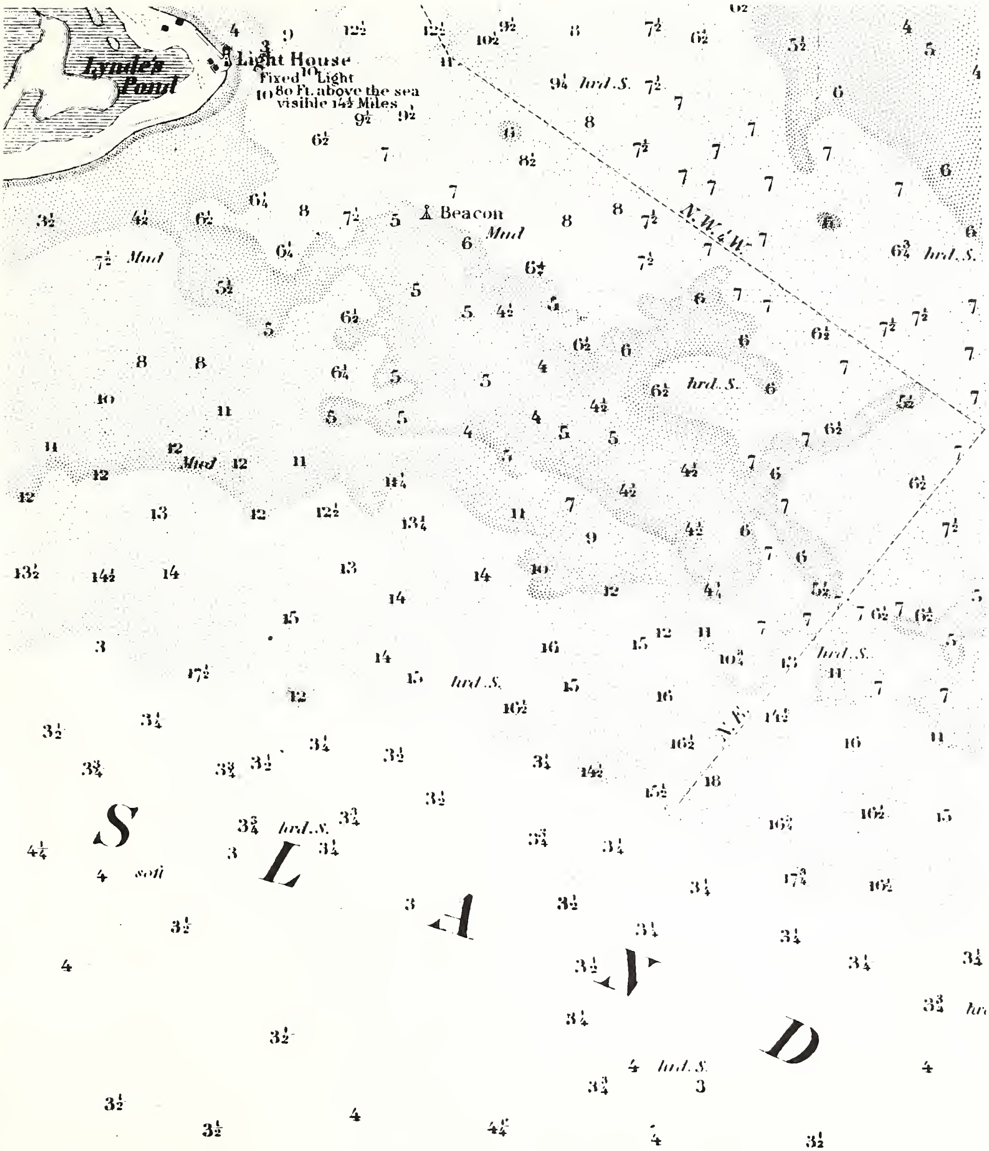


FIGURE 7.—Enlarged portion of U.S. Coast Survey Chart No. 360 (1st ed.), indicating the hydrography executed along the outer navigation channel at the mouth of the Connecticut River beyond Lynde's Point in 1849 and 1851.

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being and he is hereby fully authorized, impowered and directed, forthwith to endeavour by all proper and practicable means in his power, to cause the said continental frigate to be remov'd and got over said bar and into the Harbour of Newlondon, and for that end to employ such help and assistance of men and materials as he shall find and adjudge proper and necessary. And Dudley Saltonstall, Esq^{r}, commander of said ship, and all other officers and men belonging to said ship, are hereby requested, ordered and directed, to afford said Capt. Cotton every aid, help and assistance in their power, to effect this important and necessary object and which Congress have so much at heart. And said Capt. Cotton is to use his best prudence and discretion in prosecuting this important business to prevent said ship falling into the hands of the enemy, or any other misfortune; and to make report as soon as may be to his Excellency the Governor of his doings in the premises together with the expence attending the execution thereof that the same may be defrayed and proper information immediately made to said Hon^{ble} Congress. . ." [16]

"Same . . . "On the 27th Day of February A.D. 1778.

"Resolved, That the Committee of Pay-Table be directed to draw on the Treasurer in favour of Capt. John Cotten [sic] from the sum of 100 pounds towards defraying the expence of getting the ship *Trumbull* over Say-Brook Bar &c., and charge the same to said Cotten to be in account for the purpose aforesaid. . ." [17]

"Same . . . "On Tuesday [corrected, this should read Thursday] the 3rd Day of February 1780.

"Upon the request of the Board of War, of the 18th December 1779 for two tuns of powder to supply the two frigates the *Trumbull* and *Burbon* now lying at the port of New London. . ." [18]

It is a well-known historical fact that the blockading activity of elements of the British Fleet [19] together with harassing activities by scattered land forces [20] were forever present during the war, and recurrent occupancy of Long Island Sound by British ships could have prevented escape of the *Trumbull* on previous occurrences of favorable perigean spring tides. However, arguing against any major deployment of land forces, during the period following the evacuation of British troops from Boston to Halifax, the British were primarily concerned with defending New York City.

In a 19th century book titled *Nooks and Corners of the New England Coast,* a curiously opposite situation occurring during the French and Indian War, but also showing an historical dependence on the tides, is brought out:

"The English at Saybrook Point protected the land approach with a palisade drawn across the narrow isthmus, which very high tides overflowed and isolated from the main-land. Their corn-field was two miles distant from the fort, and skulking Pequotes were always on the alert to waylay and murder them." [21]

And so, likewise, astronomically reinforced high tidal waters played an important role on several occasions during the Revolutionary War. The impact on history of the particular tide-related circumstance under discussion involved not only the subsequent somewhat limited naval action of the *Trumbull,* but also the intriguing question of just what her potential contribution *might* have been to the small and hard-pressed elements of the Continental Navy during the earlier phases of the Revolutionary War had greater advantage been taken of the intervening cases of perigean spring tides.

Captain James Nicholson was chosen to command the *Trumbull* on September 20, 1779. Cruising orders were issued to him on April 17, 1780, and the ship saw active duty during the remainder of the war.[22]

On June 2, 1780, she took up the chase of the *Watt,* a British vessel serving under letter of marque, with whom she fought a valiant battle. Significantly, in terms of the hypothetical question of her previous untried contribution to the war effort, it has been authoritatively stated [23] that, throughout the entire period of the Revolution, this particular conflict ranks a close second in the severity of the battle to the fierce naval encounter between the *Bon Homme Richard* and the *Serapis,* a classic naval engagement.

Again, quoting from the *Colonial Records of Connecticut:*

"In June, 1780, one of the most hotly contested engagements fought at sea during the Revolution occurred to the northward of the Bermudas between the *Trumbull* 28, Captain James Nicholson, the ranking officer of the Continental navy, and the Liverpool privateer *Watt* 32, Captain Coulthard. After a fight of two hours and half both vessels withdrew seriously disabled, and with difficulty made their ways to their respective ports . . . the *Trumbull* to Boston and the *Watt* to New York." [24]

On August 8, 1781, while escorting 28 merchant ships, the *Trumbull* encountered the British *Iris,* a 32-gun frigate of superior strength, accompanied by two support vessels. In the ensuing one-sided engagement (fig. 8) she was compelled to strike her colors. The engagement as recounted in the *Colonial Records of Connecticut* reads:

"In July, 1781, he [Robert Morris, director of the Continental Fleet] ordered the *'Trumbull,'* 28, Captain James

Courtesy of The Mariners Museum, Newport News, Va.

FIGURE 8.—Battle between the Continental Navy frigate *Trumbull* (28) and the British frigate *Iris* (32) off the Delaware Capes on August 8, 1781, following her almost 3-year imprisonment upon, and final release from the Connecticut River bar at the time of a perigean spring tide, August 11, 1779. The second British ship is the *General Monk*.

Nicholson, to proceed to Havana with despatches, letters, and a cargo of flour. The *'Trumbull'* had scarcely cleared the Capes of the Delaware on August 8, when she was chased by the frigate *'Iris'* 32, Captain George Dawson. Encountering a storm, the *'Trumbull'* was dismasted, and thus crippled she was overtaken by the *'Iris'*. The *'Trumbull's'* crew were a sorry lot; some of them were British deserters, and others were cowardly and disaffected. It was late in the evening when the fight began. Many of the crew now put out their battle lanterns and flew from their quarters. Captain Nicholson and his officers, with a handful of seamen, bravely defended their ship against impossible odds for an hour before they surrendered.

". . . A letter from New York dated Aug. 11, 1781, informs us that 'this day arrived the celebrated rebel frigate named the *'Trumbull'*.'" [25] This terminated her war service.

CONTEMPORARY KNOWLEDGE OF PERIGEAN SPRING TIDES

In considering various other reasons why a possible practical advantage was not taken of earlier perigean spring tides to accomplish the release of the *Trumbull* from Saybrook Bar, it is important to recognize the generally rudimentary knowledge of the tides in this colonial period.

First and foremost, there should be taken into account the almost certain lack of technical awareness of either the causes or effects of perigean spring tides at this early date. To this must be added a rather limited familiarity by navigators with the technical principles underlying even ordinary spring tides. This knowledge rarely extended beyond the fact that, in accordance with a well-known rule-of-thumb, higher (spring) tides were associated with the "full and change of the Moon." Therefore, any case of perigean spring tides would not likely have been regarded as being any different from ordinary spring tides, which already had presented repeated opportunities for floating the ship free, without avail. Whether those concerned actually knew in advance of the favorable opportunity presented by this particular perigean spring tide in terms of a water level considerably above that of ordinary spring tides is, accordingly, very much a matter of conjecture.

In evaluating the comparative dearth of tidal knowledge in this early period, it is worthy of note that neither the astronomical phenomenon of perigee-syzygy nor the practical effects resulting therefrom in the form of perigean spring tides are anywhere mentioned in early editions of Nathaniel Bowditch's *American Practical Navigator,* the generally accepted epitome of navigational knowledge in this country, first published in 1802. However, the basic principle of these tides is described, together with their practical advantage to navigators in getting in and out of shallow harbors, in John Hamilton Moore's *The New Practical Navigator,* a British mariner's handbook which, although having gone through 12 English editions by 1796, was first published in the United States only in 1799. Although this work contains errors in its tables which Bowditch subsequently sought to correct, Moore precisely summarizes the nature of perigean spring tides in the following words which, because of their direct application to navigation, are appropriate both to the immediately preceding and succeeding examples of the practical importance of these tides:

"When the moon is in her *perigaeum,* or nearest approach to the earth, the tides rise higher than they do, under the same circumstances, at other times; for, according to the laws of gravitation, the moon must attract most when she is nearest the earth . . . Some of these effects arise from the different distances of the moon from the earth after a period of six months, when she is in the same situation with respect to the sun; for if she be in perigee at the time of the new moon, she will, in about six months after, be in perigee about the time of full moon. These particulars being well known, a pilot may chuse [sic] that time which will prove most convenient for conducting a ship out of any port, where there is not a sufficient depth of water on common spring-tides." [26]

Other references indicating an awareness of perigean spring tides by early philosopher-scientists—although a knowledge not necessarily shared by navigators—are given in a survey of pertinent tidal literature in part I, chapter 4 of the present work. The fact remains that, whether the *Trumbull's* rescuers knew the exact cause of this tidal phenomenon or not, they took advantage of it, with positive results.

TIDAL ANALYSIS

It will be observed that the portion of the previously mentioned condition of tidal enhancement used occurred on exactly the same day as perigee-syzygy. In the light of subsequent discussions in this volume concerning "phase age" and "parallax age" in relation to perigean spring tides (see chapter 8), it is desirable to point out that each tidal situation possesses its own local timing response to gravitational forces which must always be individually considered. This circumstance, as will be repeatedly emphasized throughout this volume, prevents the application of any too positive, all encompassing or generalized rules in connection with even closely adjoining coastal areas subject to the same tidal action. Such "station differences" become a function of harmonic constants (table 19), which are representative of local tidal responses to astronomical effects. Additional deviations from the tidal conditions which prevail at certain standard or "reference" tide stations, expressed as time and height variations in the high and low waters, also may be either positive or negative.

Tides at the mouth of the Connecticut River initially react more rapidly in their response to the influence of perigee-syzygy than do coastal locations farther south (compare with the tidal analysis following "The Battle of Port Royal Sound, S.C.," below). The peak of the perigee-syzygy tidal influence at the Connecticut River outlet actually occurs sometime *prior to* the near-coincidence of perigee and syzygy.

A modern example based on actual data available from tide tables appropriate to this location for a situation corresponding to the same time of the year, possessing nearly the same separation in time between perigee and syzygy, a similar declination of the Moon, and other factors will serve to substantiate this statement. The perigean spring tide involved in the *Trumbull's* release occurred on August 11, 1779, in connection with a near-alignment between perigee and syzygy which took place at approximately 8:00 a.m. (75° W.-meridian time) on this date. The time difference between perigee and syzygy was −20 hours (with perigee preceding syzygy) and the Moon, at new phase, was in declination +21.4.

A closely similar circumstance existed at the entrance of the Connecticut River at approximately the same time of the year, with almost exactly the same interval between perigee and syzygy (−20 hours), with perigee preceding syzygy, and the new moon in nearly the same declination (+17.6°) at the time of perigee-syzygy on July 15, 1920—for which date tide tables are, of course, readily available.

In practice, the predicted tide heights for Saybrook Light, at the entrance to the Connecticut River, and a so-called "subordinate" tide station, are referred to the primary tide station at New London, Conn., at which regular tidal measurements are made. As a further source of data, the earliest available hydrographic chart of the Connecticut River (chart No. 360 of 1853) previously referred to (fig. 5) indicates that the rise of the highest tide observed above the chart plane of reference prior to the chart's publication date was 5.4 ft.

From appropriate annual tide tables, the first of two maximum daily tidal ranges (lower low water to higher high water) at Saybrook Light around the preceding 1920 date was predicted for July 15, 1920 and was 4.8 ft, which is 0.5 ft in excess of the mean spring range, 4.3 ft, for this station. On July 13, 14, 15, 16, 17, and 18 the predicted maximum daily ranges for this station were 4.5, 4.7, 4.8, 4.8, 4.7, and 4.5 ft, respectively—above the mean spring range for 6 successive days, and still in excess of this value even 3 days after the occurrence of perigee-syzygy at 5:24 a.m. (e.s.t.) on July 15.

It is noteworthy that, in this very comparable case to that of 1779, the perigean spring tidal range not only was predicted to remain above the mean spring range for 3 days after perigee-syzygy, but the first case in excess of this range occurred even 2 days before perigee-syzygy. (Within this series, the first case of such a condition in excess of the mean spring range for Saybrook Light occurred at 7:54 p.m., e.s.t., on July 13, approximately 33½ hours before the mean epoch of perigee-syzygy.) As indicated earlier, the first instance of a maximum daily tidal range in this series was predicted for July 15, or on the same day as perigee-syzygy. This situation provides a contrast with the longer phase and parallax ages noted in connection with Port Royal Sound, S.C., on page 84.

HYDROGRAPHIC ANALYSIS

An additional technical evaluation of the *Trumbull's* design draft and the actual water depth necessary for this ship to have crossed the bar at the mouth of the Connecticut River is in order. The previously mentioned 1771 chart (fig. 4) of the Connecticut River shows the least depth of water along that portion of the channel (indicated by anchorage symbols) between the present lighthouse on Lynde's Neck and Fort Fenwick on Saybrook Point to be 18 ft (3 fathoms). However, the water depths over the bars located just outside the mouth of the river are much less. To the southeast of the ship anchorage, the water depth averages 10 ft, and over numerous bars outside the entrance it shallows to 4–7 ft.

Although shifting bottom sands make the water depth at the river entrance extremely subject to change, possibly even within a few days, the sounding data given on this early chart of 1771 (1784) are at least broadly representative of the situation as it existed on the Connecticut River in 1776. The hydrographic data of this chart, indicating navigational impediments subject to a partial offsetting by high tides, are further reinforced by data on the Coast Survey chart of 1853, which indicate a similar least depth of 7 ft at many places along the outer portions of the channel.

The chart datum for the 1853 chart corresponds to the mean low water of *spring* tides which, because of the additional depression of the low-water stage produced in these tides, is a little lower than the mean of *all* low waters used in the compilation of present-day nautical charts. However, this datum is considerably more representative in the case of perigean spring tides. The height of mean high water with respect to this spring tide datum plane as noted on the 1853 chart is 4.5 ft, and the height of mean low water is 0.6 ft, giving a mean range of 3.9 ft. By contrast, the mean spring range is listed as 5.0 ft, and, since the mean low water of spring tides has been set as the arbitrary zero point on this 1853 chart, the rise of ordinary mean high water springs according to these chart data is 5.0 ft.

Thus, realizing that the *Trumbull* would have to navigate water depths shoaling at the places previously mentioned to within 7 ft or less of the latter datum plane, and allowing for a mean rise of spring tides to 5.0 ft above this datum, only a ship having a draft of 12 ft (7 ft+5 ft) or less could cross these bars even at ordinary spring tides.

Although profile plans for the *Trumbull* have been determined by the present writer to be unavailable from either U.S. Navy or British Admiralty sources (late in the Revolutionary War, as previously noted, the ship was captured by the British) it is stated in Howard I. Chapelle's *The History of the American Sailing Navy* that it may be assumed she was of the standard design for a 28-gun frigate approved by the Marine Committee of the Continental Congress.[27] A sister ship of this class was the frigate *Virginia* constructed at the shipyard of George Wells in Baltimore in 1776, and which, after being blockaded by the British for more than a year, also ran aground in the Chesapeake Bay in 1778. Outboard profiles for this vessel are available in Chapelle's previously mentioned book. Scaling from the waterline on these plans gives a full-load draft (ready for service) of 18 ft 4 in. Without stores, provisions, or armament, and stripped of all extraneous weight other than that necessary to make the ship sailable, the draft, in the opinion of a NOAA naval architect, would probably have been reduced to a maximum of 14 ft.

However, in the narrow confines of the upper reaches of the Connecticut River, the square-rigged vessel, if under sail, would not be able to tack, and a following wind would also mean an offshore wind which, if strong, would depress the height of the tides at the river entrance. To negotiate the narrow, curving portions of the river, she would have to be towed by small boats. This would permit the ship to be initially stripped of top hamper, rigging, and sailing gear (some control ballast would have to be retained), and would reduce her draft to about 12 ft 8 in., but spars, sails, and other heavy gear would subsequently again increase the draft in the sea-ready condition in which she grounded on the bar.

From a consideration of the tidal data specified earlier, the maximum depth of water available across the bar at the river mouth, even at ordinary spring tides, would be 12 ft.

Assuming a forward trim and negligible pitch movement of the ship, it would still be necessary, in these only poorly sounded and as yet basically unsurveyed waters, to allow 2 to 3 ft of keel clearance to accommodate local channel-bottom variations and to ensure a safety precaution against grounding. Considering the extra buoyancy that could have been provided by a "camel," a rudimentary calculation shows it would have required more than 250 water-tight hogsheads (63-gallon capacity) first partially filled with water, and then successively submerged, lowered into position beneath the ship, and pumped completely free of water, to raise the *Trumbull* by only 1 ft. Even allowing for the buoyancy provided by such an extensive flotation gear, therefore, it is evident that the additional water depth created by a perigean spring tide would be necessary to allow the *Trumbull* to clear the bar—and this is, obviously, the opportunity that was utilized in 1779.

* * * * *

The Second Battle of Charleston Harbor

The bar outside the harbor at Charleston, S.C.,—like that of the previous example (and another at the entrance to New York Harbor)—was instrumental recurrently throughout the Revolutionary War in impeding the sailing activities of deep-draft men-of-war. In the case of Charleston, tidal circumstances connected with the astronomical phenomenon of perigee-syzygy played an important role in the second siege of this city in 1780. (The first British attempt to lay siege to Charleston on July 4, 1776 had failed.) Although a matter not directly accounted for in history, the second attempt by the British to capture this southern port was undoubtedly aided by a perigean spring tide.

Arriving off Charleston Harbor at the beginning of March 1780 after needed ship repairs at Savannah, Ga., the British found that, because of the deep drafts of their vessels, the depth of water in the entrance channel (fig. 9) was such that it was impossible to cross the offshore bar. They were compelled to stand off the coast for more than 2 weeks, hopefully awaiting a better opportunity at the next high water springs. Probably unaware of the special nature of the circumstance, but taking advantage of the augmented high waters resulting from a pseudo-perigean spring tide occurring on March 20, 1780, they succeeded in negotiating the bar with a major naval attack force, including a 50-gun frigate, two 44's, and four 32's.

The significant aspects of this naval engagement were told in a subsequent report by Vice-Admiral Marriott Arbuthnot to the British Admiralty, dated May 14, 1780:

". . . Preparations were next made for passing the squadron over Charles-town bar, where [at] high water spring tides there is only 19 feet water. [Compare with actual sounding data appearing on the two charts (figs. 10 and 11) compiled by different sources shortly after this siege.] The guns, provision and water were taken out of the *Renown, Roebuck,* and *Romulus* to lighten them, and we lay in that situation on the open coast in the winter season of the year, exposed to the insults of the enemy for 16 days before an opportunity offered of going into the harbour, which was effected without any accident on the 20th of March, not withstanding the enemy's galleys continually attempted to prevent our boats from sounding the channel . . ." [28]

The perigean spring tides of which use was made on this occasion occurred as a result of a pseudo-perigee-syzygy situation having a mean date of March 19.65, 1780, with a separation between perigee and syzygy of approximately —37 hours. Significantly, the British had been unable to make use of the preceding set of spring tides about March 6, which would have occurred near lunar apogee

Courtesy of William L. Clements Library, University of Michigan

FIGURE 9.—Hydrographic chart of Charleston Harbor, S.C., prepared by the British engravers, Sayer and Bennett, as a documentation of the tide-assisted penetration of harbor shoals and second siege of Charleston by the British, 1780.

and whose high-water levels would, therefore, be even somewhat less than those of ordinary spring tides (the average situation at perigee-quadrature, discussed at length in part II, chapter 5). The March 6 tides were also accompanied by quartering offshore winds, as noted below.

The attendant circumstances were described in editions of the *Pennsylvania Packet* for April 25 and May 2, 1780:

"March 19.—The British under General Clinton, now encamped on James Island, seem to wait for the shipping which lay off the bar, and have been disappointed at the last springs by south-west winds, which kept down the tides so that they cannot get over. This day the springs are at the highest, but the weather so hazy that they will scarcely attempt it, and it will probably clear up with unfavorable winds. We begin to hope that Province [Providence] has interposed a second time to prevent their getting over until we are ready. If they should get over either now or hereafter, there will probably be the hottest contest that has happened this war, just off Fort Moultrie. The British ships destined to come in are said to be the *Renown,* fifty guns; *Roebuck,* forty-four; *Blond,* thirty-two; *Perseus,* twenty and *Camilla,* twenty . . ." [29]

"March 20.—This morning the British got their ships over the bar. They consist of ten vessels of force, from twenty guns to a sixty-four, as some say, others a fifty. . . ." [30]

This successful passage over the Charleston bar and subsequent victorious attack by the British upon the American fleet confined within the harbor—followed by the second Siege of Charleston—resulted in the capitulation of the American ground forces under General Benjamin Lincoln on May 12, and the capture of the Continental ships *Providence, Boston,* and *Ranger,* composing major elements of Commodore Whipple's squadron. American naval vessels destroyed and sunk were the *Briscole,* 44 guns, *General Moultrie,* 20 guns, and *Notre Dame,* 16 guns.

TIDAL ANALYSIS

A modern 1974 tidal circumstance possessing conditions approximately comparable to those encountered in the second Siege of Charleston will serve to illustrate the tactical importance of the tides in this 1780 occurrence for which tide tables are not available.

Around the date October 13, 1974, a pseudo-perigean spring tide similar to that of March 20, 1780 occurred, related to a phenomenon of perigee-syzygy whose mean alignment took place at 9:06 p.m. (e.s.t.), on October 13, with a separation of —68 hours (perigee preceding syzygy by this amount).

It is noteworthy that even this considerably larger separation-interval (selected purposely, in this early chapter, as a test case for the practical range of perigean spring tide influence) is still sufficiently small to produce significant amplitude increments in the tides. This may be seen by comparing the high water and daily range data of table 6 with the corresponding values for mean high water springs and mean spring range in the second following paragraph.

The wider separation-interval in the test case, combined with other dynamic factors is, in turn, responsible for the circumstance that the lunar geocentric horizontal parallax at the mean epoch of perigee-syzygy on October 13.88, 1974 was only 59′48.55″ compared with 60′43.8″ on March 19.65, 1780.

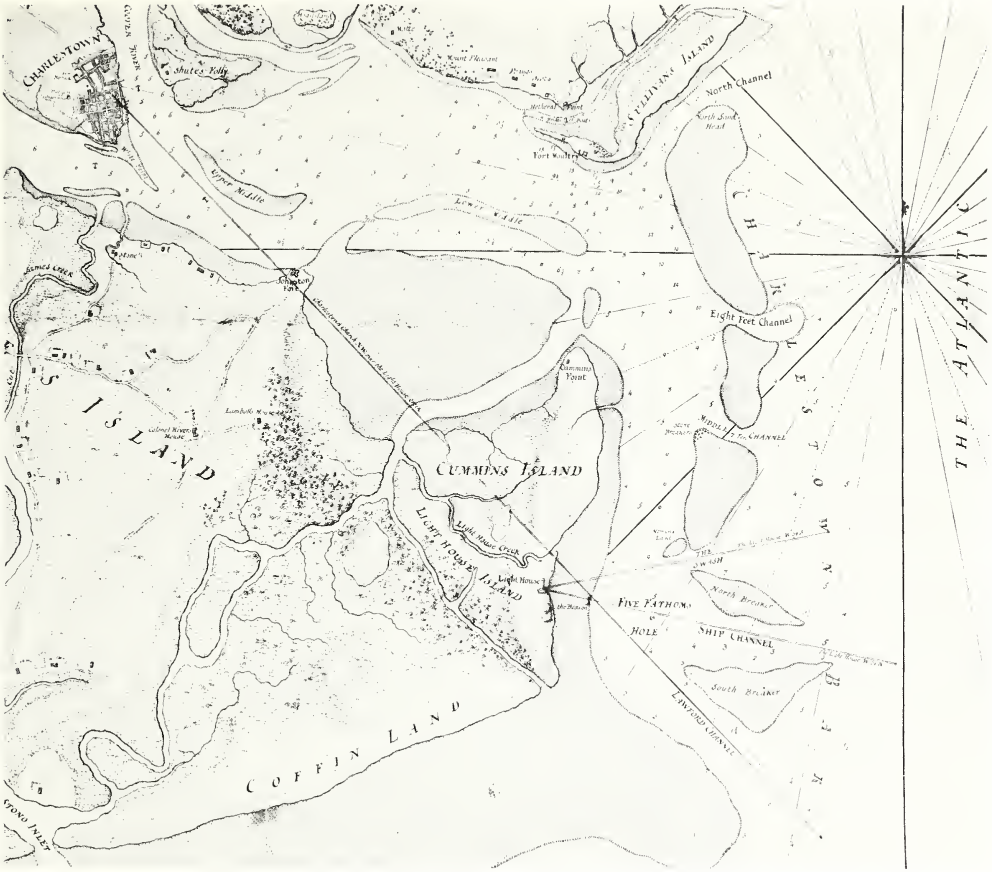
These facts give tacit but demonstrable support to the assumption of yet further increased tide-raising effects from the smaller -37^h interval which occurred in March 1780. As will be established in subsequent chapters, the Moon's proximity to the Earth and the astronomical factors which lessen this distance are the foremost causes for augmentation of tidal heights. The data of table 6 for October 1974 are, therefore, values safely on the small side in terms of the enhanced astronomical tidal situation in March 1780.

At Charleston Harbor, the corresponding predicted higher high waters (HHW's), lower low waters (LLW's), and maximum daily ranges given in the tide tables were:

TABLE 6.—*Comparative Tides at Charleston Harbor, S.C. October 13–19, 1974*

Date	Time	HHW	LLW	Maximum Daily Range
	(*e.s.t.*)	(*ft*)	(*ft*)	(*ft*)
October 13........	0542	6. 4	—0. 2	6. 6
October 14........	0634	6. 7	—0. 4	7. 1
October 15........	0725	6. 8	—0. 5	7. 3
October 16........	0815	6. 8	—0. 5	7. 3
October 17........	0901	6. 7	—0. 4	7. 1
October 18........	0948	6. 4	—0. 1	6. 5
October 19........	1034	6. 1	+0. 2	5. 9

It will be observed that the first of two maximum heights (HHW's) for these perigean spring tides was predicted for October 15 at 7:25 a.m. (e.s.t.), approximately 34 hours after the perigee-syzygy that occurred at 9:06 p.m. (e.s.t.) on October 13. This accords very closely with the circumstances under which the British crossed the Charleston bar at HHW on March 20, 1780, the next day after the pseudo-perigee-syzygy on March 19.



Courtesy of Library of Congress

FIGURE 10.—Hydrographic chart of Charleston Harbor, S.C., published by the House of Fayden in Philadelphia, May 27, 1780, 2 months after the successful navigation of the entrance shoals by British frigates at the time of a perigean spring tide, March 20, 1780.

On the chart (fig. 10) published by the House of Fayden in Philadelphia on May 27, 1780, 2 months after the second Siege of Charleston, the datum for mean high water spring tides at Charleston is given as 5.6 ft above the mean low water chart datum. Corroborating this early value, the figure given for mean high water springs at Charleston (Custom House Wharf) in modern tables is also 5.6 ft above the same chart datum. The corrections to the height of HHW for North Jetty, at the entrance to Charleston Harbor and nearby points on the outer coast of South Carolina are, consistently, 0.0 ft. The mean spring tidal range at Charleston is 6.1 ft.

In this comparative situation, the predicted higher high water at Charleston Harbor therefore remains in excess of the value for mean high water springs—and even above that representing mean spring range—for periods of 7 and 6 days respectively, around perigee-syzygy. Likewise, the maximum predicted tidal range at Charleston remains above the mean spring range for 5 days after perigee-syzygy, even under these conditions involving a comparatively large (~68-hour) separation in time between the two components. The separation-interval for the 1780 example was somewhat smaller, approximately ~37 hours, a factor contributing still further in this case toward the raising of high tides.

Closely supporting the above analysis is the footnote of tidal information contained on the earliest chart of Charleston Harbor prepared by the Coast Survey (Chart No. 432, 1st edition, 1855) where the highest tide of record at Castle Pickney on Charleston Harbor up to that date is given as 7.32 ft (observed on April 15, 1851—accompanying another pseudo-perigean spring tide). On this same Coast Survey chart, the mean daily tidal range at this location is given as 6.01 ft. The level of mean low water springs is specified to be −0.19 ft below that of mean low water (the chart datum), and the mean range of spring tides is given as 5.81 ft. Hence, the rise of mean high water springs above mean low water is $5.82-0.19=5.63$ ft. The minimum navigable water depths past the bar outside Charleston Harbor just prior to the second Siege of Charleston can now be correlated with these tidal data.

HYDROGRAPHIC ANALYSIS

A second chart (fig. 11), of the water depths inside and outside Charleston Harbor, prepared by the British engravers Sayer and Bennett in 1780, within a few months after the second siege of this city, is more specific in its hydrographic data than is the Fayden chart. According to a premetric practice in nautical chart representation, all water depths up to 18 ft are given on the chart in units of feet; depths in excess of 18 ft (3 fathoms)—and, specifically, those along designated navigation channels—are specified in fathoms (1 fathom = 6 ft). However, the depths of water over shallow bars or submerged reefs (which are indicated on the chart by stippled areas outlined by dotted lines) are also given in feet, printed alongside the submerged features. Having been prepared long before this standard procedure went into effect, the two 1780 charts utilize a slightly different manner of presentation. With the exception of a few shoal-water passages where the water depth is specifically indicated as being in feet, all soundings thereon, regardless of location, are given in fathoms.

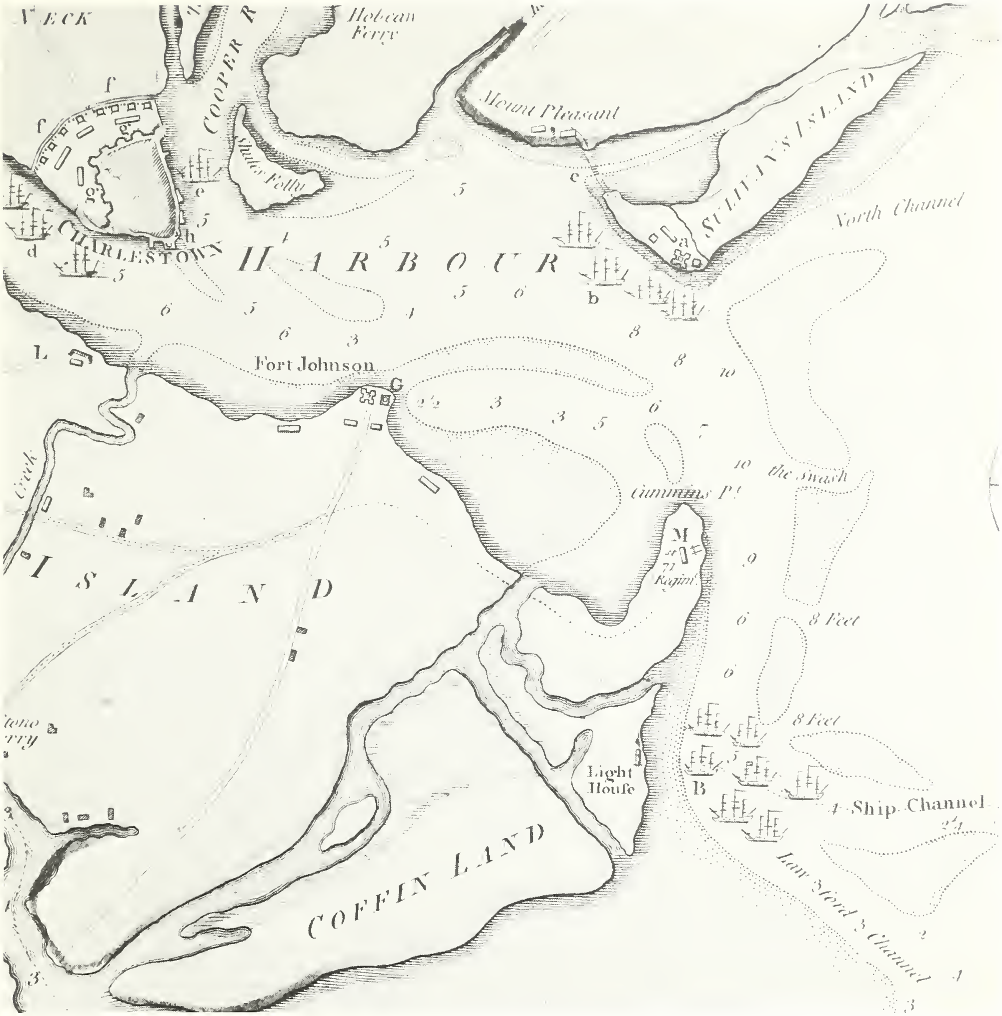
Thus, the shallowest water depths between two bars bracketing the designated Ship Channel (which the British used) leading into Charleston Harbor are seen to range from 2 to 3 fathoms (12.0 to 18.0 ft), with the water depths over the bars being only 8 ft. The first values appear on the chart shown in fig. 10; the second value is given in fig. 11. These quantities are also generally confirmed on the same portion of the earliest Coast Survey chart of Charleston Harbor published in 1855 (figs. 12, 13), where the minimum channel depth is shown to be 3¼ fathoms. Despite the constantly drifting bottom sand, both inside and outside the harbor, these charts provide an interesting comparison of the general bottom configuration at two epochs 75 years apart. Their general similarity is also germane to the assumption of an average reproducibility of sea-level datums over extended periods of time, necessarily employed throughout these various analyses.

To provide the most accurate information possible concerning the ships involved in this siege, an inquiry was directed to the National Maritime Museum in Greenwich, England, relative to the drafts of the ships *Renown, Roebuck,* and *Romulus.* The report indicates that:

"Unfortunately, the official lists of ships in possession of the Admiralty do not give the drafts of 1780, but do so in the 1790's, by which time the *Renown* was out of service. Her sister ship, the *Portland,* is stated in a list of 1795 . . . to have a draft of 10′6″ forward, 15′7″ aft. . . . The *Roebuck* and the *Romulus* were somewhat similar ships, draft 10′8½″ forward, 14′½″ aft. It is not, however, specified exactly what these measurements describe, except that they are 'light'." [31]

The latter statement would imply an out-of-service draft, discounting any load of gunpowder, stores, shot, or cannon. The previously quoted memorandum from Vice-Admiral Arbuthnot indicates that guns, provisions, and water were taken out of these ships before Charleston to lighten them. No mention is made in Admiral Arbuthnot's account relative to the ships making rendezvous to refit, for example, in the available Five-Fathoms Hole after crossing the bar. Inasmuch as a combat status was resumed immediately on crossing the bar, it is unlikely that more than the bare minimum of tactical gear, shot, and ordnance was removed, and that the major portion of the ship's heavy combat-readiness equipment remained. Certainly it would be impractical, under the contingencies of time and a hostile environment, to remove more than the guns located on the top deck.

It is, therefore, clearly mandatory that (in a directly opposite case to that of the *Trumbull*) an additional 1 to 2 ft must be added to the previously specified light drafts of the *Renown, Roebuck,* and *Romulus* under such conditions of near-combat readiness, to compensate for their considerably stripped-down conditions when out of service. A minimum operational draft for the *Renown* before Charleston of 16½ to 17 ft aft can, therefore, safely be assigned.



Courtesy of William L. Clements Library, University of Michigan

FIGURE 11.—Enlarged portion of Sayer and Bennett chart of Charleston Harbor (fig. 9), emphasizing the shoals at the entrance through which the deep-draft British frigates were forced to pass. Comparison of water depths with those of figure 10 shows a close agreement between these charts published respectively in England and America.

In addition, subject to the small-boat harassment which Vice-Admiral Arbuthnot mentions, and to prevent any further buildup of resistance by American forces, there was the necessity for the British to accept those weather and tide conditions which offered the earliest possible opportunity for crossing the bar, in contrast to a permissible period of waiting for favorable conditions in the Connecticut River example.

Choppy seas coupled with a possible light ground swell might readily be produced by the unfavorable winds men-

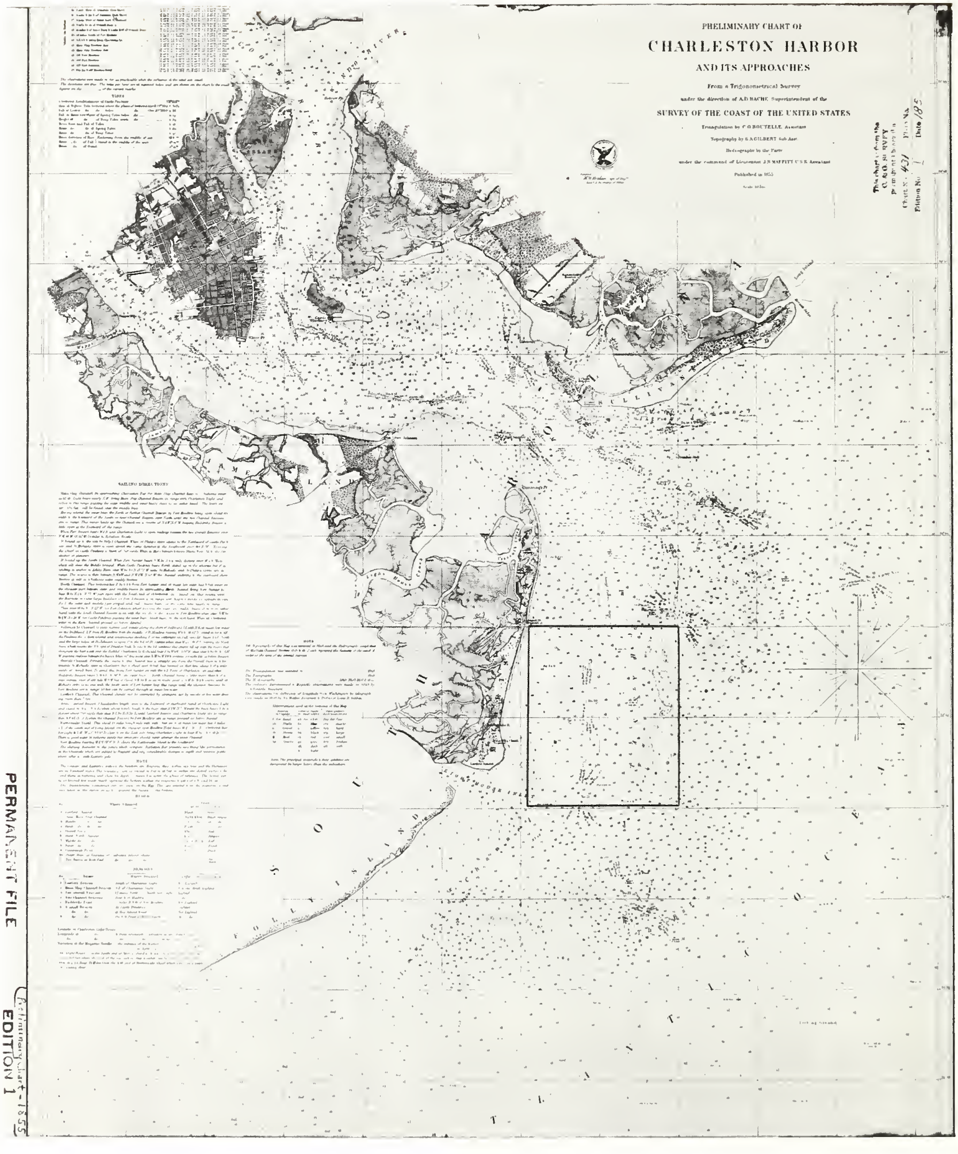


FIGURE 12.—Preliminary chart of Charleston Harbor and its approaches (C&GS Chart No. 431, ed. No. 1) published by the U.S. Coast Survey in 1855, containing significant tidal data and datum planes. The small boxed area indicates the portion of the chart enlarged in figure 13.

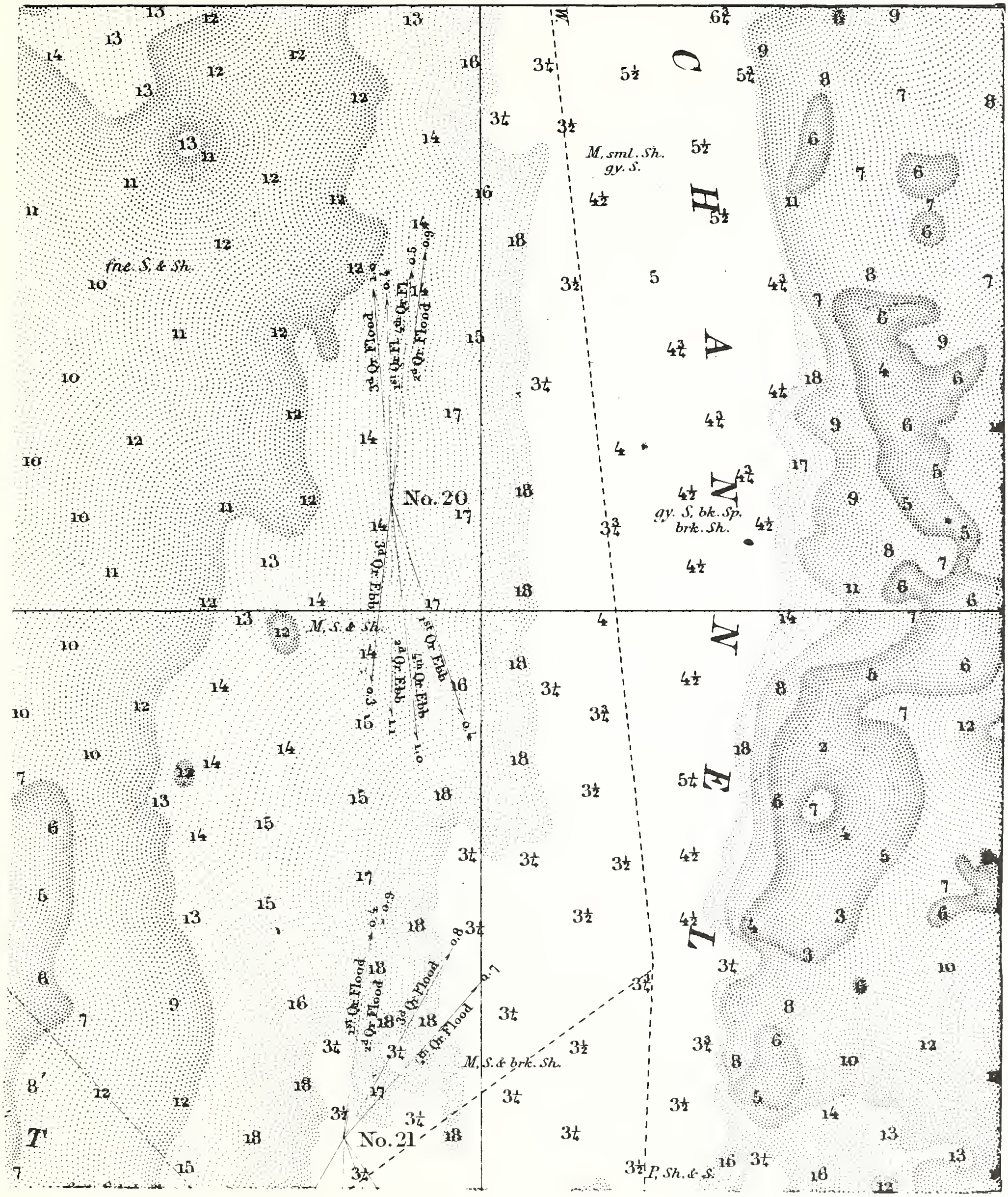


Figure 13.—Enlarged section of C&GS Chart No. 431, ed. No. 1, of Charleston Harbor (fig. 12), showing soundings in the southern portion of the main ship channel, with a minimum depth of 3¼ fathoms.

tioned in the previously quoted *Pennsylvania Packet* article. The movement of this swell over the prominent shoals in this area could cause "blind rollers." These, in turn, would cause the entering ships to heave and pitch and would require additional keel clearance to prevent running aground. Thus, in order to ensure a reasonable margin of safety in these little-known waters, the largest British ship, the *Renown* (even with a partially lightened condition) would have needed a water depth of at least 20 ft to negotiate the channel.

Choosing, for the sake of impartiality, that contemporary British chart which shows even the greater of the two values ($2\frac{1}{4}$ fathoms or 13.5 ft) for the shoal-water depth in the channel, the required tidal height above mean low water for safe navigation must, therefore, have been $20-13.5=6.5$ ft. This is a condition which, according to the data appearing on the 1855 Coast Survey chart, is not attained even at ordinary spring tides, whose mean height at Castle Pickney on Folly Island is given as 5.63 ft. Modern tide tables indicate that the difference in high waters between Folly Island and Sullivans (Sulivan's) Island on the outer coast is 0.0 ft. The necessary additional rise in tide height to provide a navigable water level of 6.5 ft (or 8.0 ft, according to the second British chart) above mean low water could have been provided only by the perigean spring tide at this second Siege of Charleston.

* * * * *

Two further episodes in U.S. naval history, the one similar, the other involving a different operational application, but both related to the amplitude-increasing aspects of perigean spring tides, occurred during the Civil War.

The Battle of Port Royal Sound, S.C.

This third instance in which perigean spring tides unquestionably exercised an important influence upon an event in American history forms a desirable technical extension of the preceding example. It is characteristic of a tidal property derivable from table 19 that, on the south Atlantic coast of the United States, perigean spring tides tend to follow, by 1 to $1\frac{1}{2}$ days in time, the near-coincidence between perigee and syzygy which produces them.

On October 29, 1861, a contingent of the Union Fleet, known as the South Atlantic Blockading Squadron, sailed southward from Norfolk, Va., subject to sealed orders. This largest naval armada ever constituted in American history, up to that time, consisted of 50 fighting ships under the command of Flag Officer Samuel Francis Du Pont. Its destination, Port Royal Sound, S.C., had been determined by the Federal Government to have the greatest possible strategic value in pushing the war against the South.

The armada was peremptorily scattered en route by the first lashings of a violent coastal gale (some historical sources have variously described it as a hurricane)[c] which, moving northward, subsequently struck inland and caused severe tidal flooding along the New Jersey coast. (See the list of historic tidal floodings of North America in table 1 under the date November 2, 1861.)

The date of mean perigee-syzygy upon this particular occasion (with only 1 hour separating the two components) was November 2, 11.5 hours, 75° W.-meridian time (eastern standard time not yet being in use). This very near-coincidence of perigee and syzygy was combined with an extremely close proximity in the distance of the Moon from the Earth at the time, represented by the large geocentric horizontal parallax of 61′27.6″ (see table 16)—yielding a *proxigean spring* tide.

As explained in the subsequent tidal analysis of this event, because of the normal "phase age" and "parallax age" between the close alignment of perigee and syzygy and the associated increased tidal effects in these southern coastal waters, the maximum augmented tidal effects could be expected approximately 1 day after perigee-syzygy—or in the early morning hours of November 3. As further confirmed by data taken from modern tide tables available for this location, the accompanying increased tidal ranges caused by the perigee-syzygy alignment would also continue for several days thereafter, through November 4, 5, and 6.

Thus, paradoxically, the same perigean spring tides which, in conjunction with strong onshore winds, resulted in tidal flooding and severe coastal damage in New Jersey, served an advantageous purpose in the attack on Forts Walker and Beauregard, commanding Port Royal Sound. This advantage resulted from the relatively high navigational waters associated with these perigean spring

[c] In the interests of scientific objectiveness, reference should be made to the discussion concerning the necessary uncertainty in designation of early North American hurricanes—and the often more-or-less arbitrary classification thereof by experts (among whom opinions differ)—that precedes table 2. It is not the purpose of this treatise to exercise any partiality.

The disturbance in question had moved on northward from the scene of action in the present case. Hence, the exact type of storm earlier represented has no direct bearing upon the *navigational* importance of the astronomically produced perigean spring tides. These alone aided the tactical circumstance at Port Royal Sound described above. Remotely produced swell or waves were not a contributing factor.

tides as approximately 40 ships which were not too badly scattered or disabled by this same storm off Cape Hatteras made rendezvous some 10 miles off Port Royal Sound early on Monday morning, November 4.[32] (Several otherwise reputable historical reference sources give this date as November 5 and the date of crossing the bar as November 7, both of which are incorrect.) All artificial aids to navigation (position-fixing targets, buoys, lighthouses, etc.) already had been removed by the rebel forces and, on this low coastline, no significant features of natural topography were available to serve as identifying navigational landmarks.

Much battered by the gale, the remnants of the original fleet assembled one by one, and anchored outside Port Royal Sound (fig. 14), where the passage of these deep-draft vessels across the bar at the entrance now posed a serious operational problem. In the months of preparation that had preceded this great combined deployment of naval and army forces to the south, it obviously had been planned to arrive and enter the harbor at the time of the spring tides associated with the new moon of November 2. It is questionable whether, in the existing state of knowledge, it was recognized, or definitely brought into consideration, that this date also represented an occasion of perigean spring tides.

The storm had delayed the mission by 2 days. Already the lifespan of the presumed ordinary spring tide (which normally reaches a maximum and declines within a day or two) was fast disappearing. This undoubtedly explains the sense of urgency for immediate passage across the bar indicated in the eyewitness account given below. However, as shown in the subsequent tidal analysis of this episode, perigean spring tides last considerably longer.

The hydrographic survey vessel *Vixen,* a side-wheel steamer which had been obtained by the Union Navy from the Coast Survey for inshore sounding operations, was ordered into action. It had been brought along to Port Royal Sound (then known as Port Royal Bay or simply Royal Bay) for just such a contingency as they now faced. During the ensuing activities of making soundings by leadline, buoying the channel, and leading the fighting ships across the bar, the influence of the perigean spring tide soon became known, as is referred to obliquely and without elaboration in the official reports of the expedition. Charles O. Boutelle, Assistant, U.S. Coast Survey, was in charge of these sounding activities and, in a letter dated November 8 from Port Royal Bay, he wrote to the Superintendent of the Coast Survey as follows:

". . . The *R.B. Forbes* came to me [on Monday, November 4] to say that the *Augusta* and *Dale,* steam gunboat and sloop-of-war, were outside. I reported the fact to the commodore, and he expressed so earnest a wish to get them in before the attack that I determined to bring them in at once, though night had already come on. The *Augusta* draws 15 and the *Dale* 16 feet. We ran down about 8:00 p.m., and anchored a boat, with a Fresnel lantern in it, at the entrance of the channel. I then went to the two vessels and communicated the commodore's orders. Both captains were ready to go in if I would take the responsibility of leading them. The *Augusta* took the *Dale* in tow, and we passed in without trouble, having no cast less than 19 feet [the evening lower high water associated with the perigean spring tide would have been about 9:25 p.m. on this date], and I had the satisfaction of reporting to the flag-officer their arrival at half past eleven p.m. Running outside again I anchored the *Vixen* at the entrance in readiness to bring in the *Ericcson* and the *Baltic,* drawing 20 and 22 feet . . .

". . . At sunrise [Tuesday, November 5] we anchored a large spar buoy at the entrance of the south channel. Mr. Platt and Mr. Jones, 1st and 2d officers of this vessel, were then sent on board of the *Baltic* and *Ericcson,* respectively, and I led in with the *Vixen* at half flood [the morning higher high water for the perigean spring tide of this date would have been about 9:50 a.m.]. We had no cast less than 27 feet, and I can say with certainty that vessels drawing 25 feet may come in at all ordinary tides [an oblique reference to the fact that, at 27 feet and more, the existing tides were in excess of "ordinary" (including spring) high tides—see below] . . .

". . . The *Wabash* started for the batteries at 8:30 a.m. . . ." [33]

As recounted above, during the lower high water in the late evening of Monday, November 4, the *Vixen* guided two smaller ships over the bar. On the morning of Tuesday, November 5 (with higher high water about 9:50 a.m.), aided by the effects of the perigean spring tide, she led the remainder of the large-draft vessels of the fleet, with the flagship *Wabash* (fig. 15) second in line, across the bar, "with only a foot or two to spare." [34]

". . . As they ran past vessels that already had crossed, cheers rang out over the water. . . After this came some delay until buoys could be placed around the dangerous shoal. . . Even then, as the next succeeding low tide [deepened by the effect of perigean springs] approached . . . the *Wabash,* trying to fix the outlines of

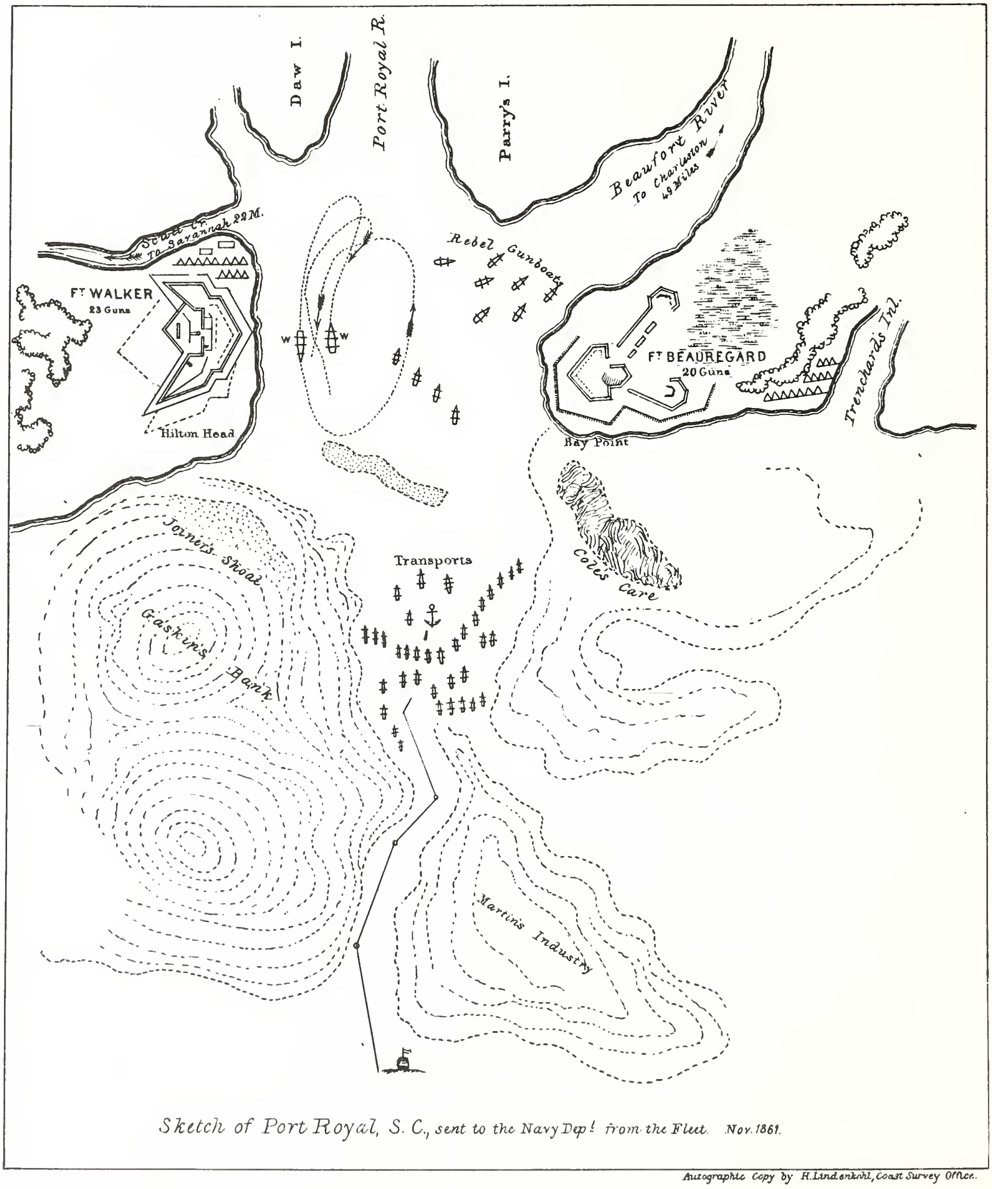
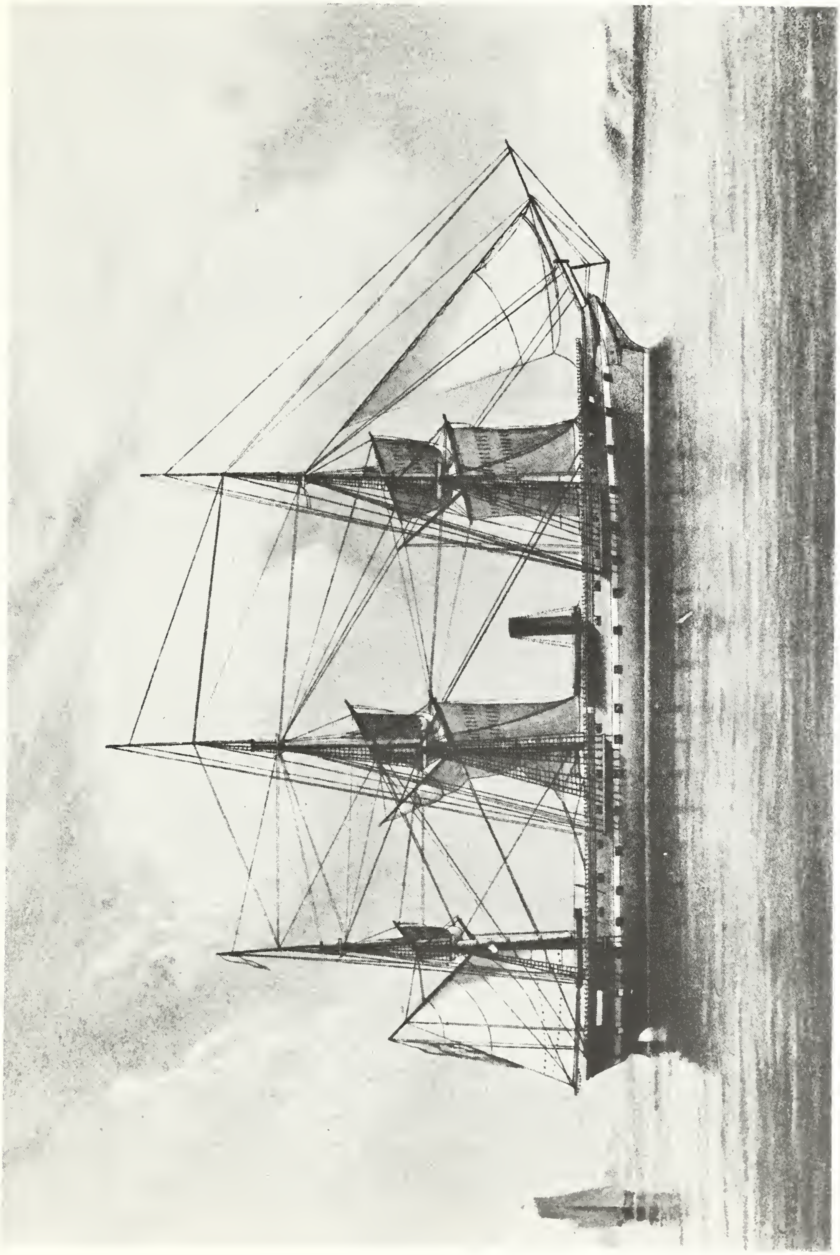


FIGURE 14.—Sketch of Port Royal Sound, S.C., and the Union naval maneuvers before Fort Walker, prepared by a Coast Survey technician aboard the hydrographic survey ship *Vixen* during this Civil War engagement in November 1861. The chart shows the location of the entrance channel between Gaskin's Bank and Martin's Industry depicted in greater detail in figure 16.



Courtesy of The Mariners Museum, Newport News, Va.

FIGURE 15.—Lithoprint of the first-rate battleship *Wabash*, flagship of the Union fleet in the attack on Fort Walker and Fort Beauregard during the Battle of Port Royal Sound (or Port Royal Bay) on November 7, 1861. This battle followed a successful crossing of the entrance bar 2 days previously, utilizing a perigean spring tide.

the fort before dark, pushed on too rapidly and grounded. By the time she was free again, Du Pont decided it was too late to proceed, and the squadron was signaled to withdraw out of gunshot for the night. . ." [35]

Although the planned attack was delayed on the next day by bad weather, on November 7 Fort Walker was captured, and later, Forts Royal and Beauregard. Through this success at Port Royal, the Federal Navy secured access to, and control of, all inland waterways between Savannah and Charleston. The naval blockade of the South was thereby greatly enhanced.

TIDAL ANALYSIS

The depths of the actual soundings made on November 4–5 empirically confirm that a perigean spring tide was present and that its effects extended several days after the time of mean perigee-syzygy at this particular location on the east coast of the United States.

Supplementary tidal data contained on the contemporary nautical charts mentioned in the next section support this statement. Descriptive notes accompanying the preliminary chart, of which fig. 16 is an enlarged section, indicate that the mean rise and fall (i.e., the mean range) of high water springs in Port Royal Sound is 7.3 ft. The average fall of low waters associated with spring tides below the chart datum (plane of reference) of mean low water is -0.9 ft. This gives a reduced value for mean high water springs of $7.3-0.9$ or 6.4 ft above the chart datum of mean low water. The rise of the highest observed high water above the chart datum prior to the date of the chart is given as 8.6 ft, and the fall of the lowest tide observed below this same plane of reference is -2.0 ft, indicating a rise of $8.6-2.0$ or 6.6 ft above mean low water. The latter values provide an essentially accurate means of determining the incremental variations ($8.6-6.4=2.2$ ft) and ($-2.0-(-)0.9=-1.1$ ft) caused by perigean spring tides. These differences were probably supplemented in the extreme instances noted above by the effects of onshore and offshore winds, respectively.

Based on the sounding data provided for mean low water on the aforementioned preliminary chart, the sum of this low water depth and the height of the high water, both subject to the effects of a perigean spring tide (i.e., $19.5 + 8.6 = 28.1$ ft) is, in fact, necessary to account for the water depth measured by the *Vixen* at Royal Bay near the time of higher high water on the morning of November 5. The statement contained in the hydrographic report "nowhere less than 27 feet" also conforms with, and confirms the existence of, a perigean spring tide. An ordinary spring tide would provide only $19.5 + 6.4 = 25.9$ ft at mean high water springs.

As before, actual tide data for Port Royal will be taken from available modern sources for a situation having exactly the same time difference between perigee and syzygy as occurred on November 2, 1861. A comparison of the data for Port Royal and Saybrook Light will reveal, for these respective cases, a basis for individual analysis of (1) the lag-time influence between perigee-syzygy and the occurrence of the maximum influence of perigean spring tides, and (2) the total duration of time over which the effects of these perigean spring tides are felt. These two factors are the combined result of geographic location, hydrography, and astronomy.

In order to establish tides at Martin's Industry at the mouth of Royal Bay which are similar to those of November 2, 1861, a closely comparable perigee-syzygy situation occurring on January 8, 1974, has been chosen. On this date, perigee-syzygy had a separation of -2 hours, the geocentric horizontal parallax was 61′30.0″, and the declination of the Moon was $+20.4°$. Very closely spaced times between perigee and syzygy and close proximities of the Moon to the Earth, among other factors, are seen to be common to both the 1861 and 1974 instances. Both will later be described as *proxigean spring tides.*

Daily high- and low-water predictions for Martin's Industry are calculated by reference to Savannah River Entrance, the most representative tidal station at which regular measurements are made. From the tide tables, the mean spring range at Martin's Industry is 7.6 ft. However, responding to the effect of the close perigee-syzygy which took place on January 8 at 6:48 a.m. (e.s.t.), the predicted maximum daily ranges for the perigean spring tide occurring at Martin's Industry on January 8, 9, 10, 11, 12, and 13 were, respectively, 9.6, 9.8, 9.6, 9.1, 8.3, and 7.3 ft. The corresponding predicted high waters for these dates were, respectively, 8.0, 8.0, 7.8, 7.5, 7.0, and 6.5 ft. The value of mean high water springs previously given is 6.4 ft.

Therefore, for this almost exactly comparable situation to that of 1861, the higher high water would have remained in excess of mean high water springs on, and for fully 5 days after, the date of perigee-syzygy. This accounts for the fact that the necessary height of waters required for navigation over the bar at Port Royal still existed on November 5, 1861, a full 3 days after perigee-syzygy, a situation which would not have occurred in the case of an ordinary spring tide.

Similarly, at Martin's Industry, the maximum response in tidal range to the phenomenon of perigee-syzygy took

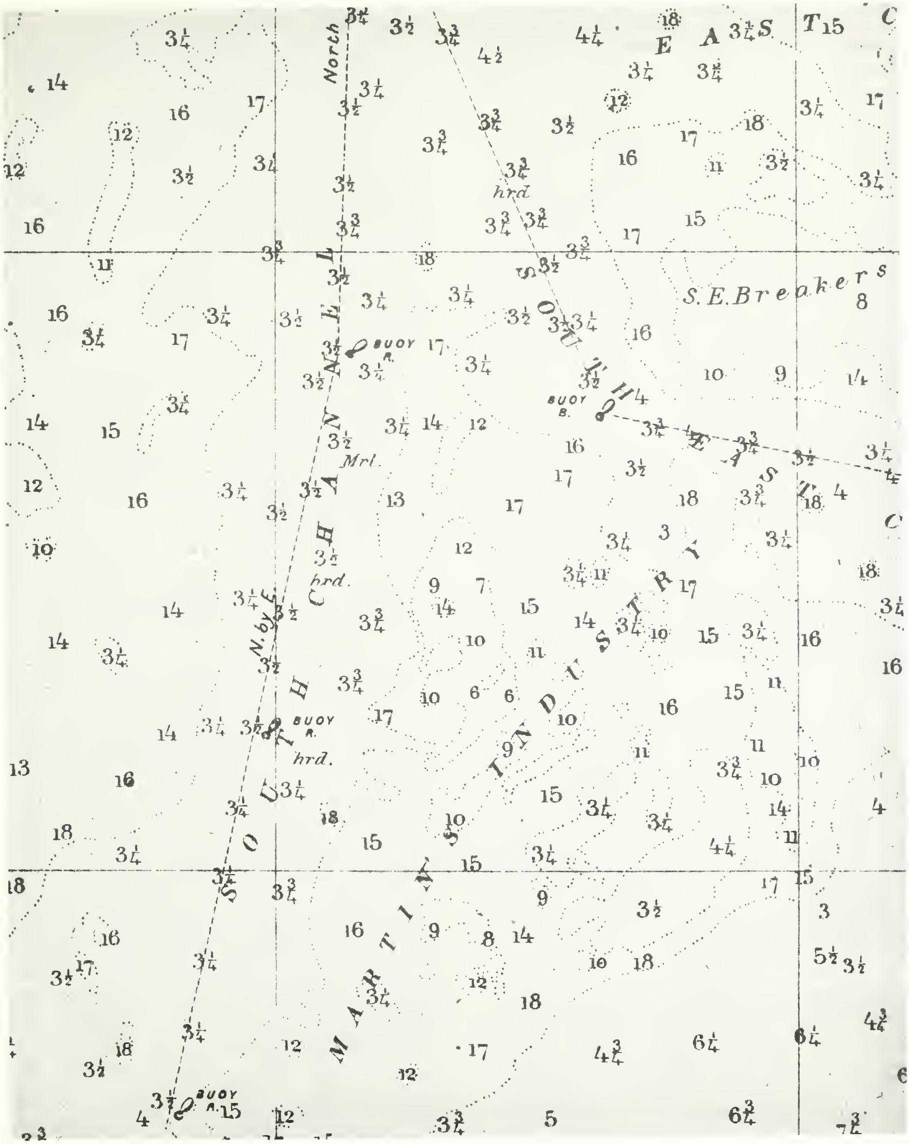


FIGURE 16.—Enlarged section of a Preliminary Chart of Port Royal Entrance (Sketch No. 26 in the annual *Report of the Superintendent of the Coast Survey for 1862*) based on soundings executed in 1855, 1856, and 1862. The area represented is in the South Channel lying between Gaskin's Bank and Martin's Industry.

place, a day later, on January 9, 1974. The first of two maximum higher high waters in this series occurred on January 8, at 7:04 a.m. (e.s.t.), approximately ¼ hour *after* perigee-syzygy—whose mean epoch was 6:48 a.m. (e.s.t.) on January 8. Even this small delay is in contrast with the situation at the mouth of the Connecticut River in the previous example, where the first maximum higher high water occurred 33½ hours *earlier* than the mean epoch of perigee-syzygy. The fact that the predicted high tides at Port Royal Sound remained in excess of the value of mean high water springs (6.4 ft) for a full 5 days after perigee-syzygy also illustrates the effect of perigee-syzygy in extending the duration of spring tides, and corroborates the similar 5-day extension at Saybrook Light, Conn. (MHWS = 3.8 ft).

HYDROGRAPHIC ANALYSIS

A Preliminary Chart of Port Royal Entrance published in 1862 by the U.S. Coast Survey and based upon soundings executed in 1855, 1856, and 1862 (of which fig. 16 is an enlarged portion) shows the least depth of water (for a chart datum corresponding to mean low water) along both the South Channel and the Southeast Channel at the entrance to Port Royal Sound to be 3¼ fathoms (or 19.5 ft). The South Channel was used by the attacking fleet. The Southeast Channel is somewhat narrower and contains contiguous shoals shallowing to 3 fathoms.

The bar itself is about 10 miles from the headlands forming the entrance to Royal Bay. A major shoal just to the east of the South Channel and lying between it and the Southeast Channel forms the most seaward part of the bar, and is called Martin's Industry. The water shoals to a depth of 6 ft here at mean low water (even less, if offshore winds prevail) and, because of the effects of increased range, falls to 4 ft at low water associated with ordinary spring tides. To the west of the South Channel lie the Gaskins Banks, with depths as shallow as 14 ft, decreasing to 11 ft (at mean low water) further north where the two entrance channels converge.

DATA CONCERNING THE DRAFT OF THE *WABASH*

Precise figures on either the full-load or lightened drafts of the ship *Wabash*, flagship and largest in the fleet which crossed the bar on the morning of November 5, are not directly available. The only draft figures obtainable in connection with this vessel are those established in 1897 when the ship was stripped down and housed over as a receiving ship in the Boston Navy Yard, with her gun batteries and deck armament removed. The mean draft to the keel was then given [36] as 22 ft 9 in., which is matched by statistical data on Civil War ships contained in *Official Records of the Union and Confederate Navies in the War of the Rebellion*.[37] Here the draft figures are given as "loaded, forward, 22′6″; aft, 23′." These values are obviously low, however, when the weight of guns and armorplate is considered. Top hamper also would have added considerable displacement, bringing the full-load draft of the *Wabash* certainly somewhere more nearly in the range of 24 to 26 ft.

The South Channel traversed by the Union Fleet is 10 miles to sea from the entrance to Royal Bay. In intensified swell at such offshore distances, the heave and pitch of the vessel alone would require a safety margin of several feet for keel clearance. Thus the total depth of water required for safe passage of the *Wabash* over the bar would have been at least 28 ft. With the exception of hurricane-lifted seas, this water depth is available only as the result of the perigean spring tide conditions described in the section on "Tidal Analysis," together with favorable onshore winds.

* * * * *

The Perigean Spring Tide as an Agent of Coastal Erosion

Because of the added onslaught against the land produced both by increased current velocity and greater range in water level associated with perigean spring tides, low-lying and potentially submersible coastlines are subject to greater erosional influences under these circumstances. The actions of strong onshore winds, high waves, and swell may likewise tear at coastlines wherever these meteorologically produced factors are present. When such wind-induced conditions also reinforce a higher-than-usual tide, a greatly increased erosional influence is almost certain to occur. Marked coastline attrition may then result from both astronomical- and wind-accelerated tidal current velocities, larger sedimentary particles maintained in suspension in the water, and enhanced transport of eroded sediment away from the shoreline.

The effects of tidal erosion also are related to more forceful water impact against the shoreline, and wave scouring at greater heights and distances onshore than usual. These influences may be combined, during each reduced stage of the tides, with foreshore-undercutting at points which are lower, farther offshore, less compacted through constant shifting, and hence less resistant to erosion. Because the same intensified astronomical forces associated with perigean spring tides act upon both the low and high waters, this phenomenon is characterized by exceptionally low tides as well as exceptionally high tides. When these are combined with powerful wind action, the erosional effects of such an alternation of extreme high and low waters may be highly destructive, or even catastrophic, in contrast with the steady, degradational action of the sea which occurs continuously on all coastlines during ordinary tides. If perigean spring tides are accompanied by strong, onshore winds and swell, large portions of beachline, as well as sections of the foreshore, may be gouged and torn away.

An interesting example of the effect of coastal erosion upon an important episode in history occurred during the Civil War.

The Hatteras Campaign

Both the bold planning and ultimate success of the Hatteras Campaign undertaken by Union forces at the very outset of the Civil War are a matter of detailed historical record. It is not generally known, however, that certain definite portions of this planning, as well as a considerable degree of success in the operational aspects of the campaign, were the indirect consequence of two earlier astronomical occurrences of perigee-syzygy and their associated perigean spring tides. These precursory factors will be briefly reviewed.

On March 1, 1846, as documented in the annual *Report of the Superintendent of the Coast Survey* for 1847,[38] a severe coastal storm swept the vicinity of Bodie's Island, N.C., and the resulting tidal flooding produced several breaches on the seaward side of this narrow spit—one of a line of barrier islands composing the Hatteras Outer Banks.

The sea piled onto the land and inundated numerous portions of the Hatteras Banks. This first of a series of three severe coastal storms in the same year followed some 3 days after the maximum influence of a perigean spring tide centered around February 26 (allowing for a 1-day phase- and parallax-age at this location, as normally experienced). This tide was associated with a condition of perigee-syzygy having an approximate alignment very early in the morning of February 25, and a difference in time between its astronomical components of just over −30 hours. Because of at least a 3-day separation in time from the maximum of the perigean spring tides, the flooding produced on March 1 only started to form the previously mentioned breaches in the land.

However, a second major coastal storm occurred on September 7–8, 1846, as mentioned also in the Coast Survey annual report.[39] The Coast Survey brig *Washington,* commanded by Lt. George M. Bache, brother of the second superintendent of the Coast Survey, together with 10 seamen, were lost in this storm off the coast. Although referred to in some historical sources as a hurricane, neither Ivan R. Tannehill in his book *Hurricanes* (8th ed., 1952) nor Gordon E. Dunn and Banner I. Miller in their work *Atlantic Hurricanes* (rev. ed., 1964) include this storm among their comprehensive catalogs of true hurricanes and tropical storms.[d] The accompanying gale swept the coastline, adding its effects to a perigean spring tide whose maximum rise on this occasion had occurred less than 1 day before, as a result of a perigee-syzygy alignment having a mean date of September 5.0 (with components separated by only −15 hours). A sustained gale-force wind from the northwest on the 7th and 8th, coupled with high perigean spring tides, lifted the waters of Pamlico (then spelled "Pamplico") Sound to a height of 2 or 3 ft over almost the whole of Bodie's Island.[40] In consequence of this violent flooding action, Oregon Inlet was formed. This inlet is still called "New Inlet" in the first edition of a nautical chart of Pamplico Sound, compiled by the U.S. Coast and Geodetic Survey in 1883 (fig. 17).

Portions of the barrier spit to the south similarly were breached at a point where a comparison map of North Carolina prepared by Brazier and MacRae in 1833 (fig. 18) shows no previous permanent passage. Near Hatteras village, a variably inundated tidewater area was rendered navigationally passable overnight by the force of the rampaging waters washing back from Pamplico Sound. Still another severe coastal storm occurred during October, further scouring this southern inlet. Previously, the waters forming this narrow channel had been too shallow to permit the passage of deep-draft vessels. The larger inlet formed now possessed a sufficient depth of water to accommodate rather sizable vessels, a circumstance conducive to the development of active maritime commerce. Hatteras village provided a port for the transshipment of goods to smaller intracoastal craft more suited to ply the coastal waterways and rivers. Accordingly, Hatteras Inlet, as it was called, gradually came to outrank Ocracoke Inlet and its commercially declining town of Portsmouth in shipping importance. The least depth of water at the entrance to this newly created inlet (which persisted, despite shifting sands, over the intervening 15 years until the Civil War and thereafter) was 14–16 ft. Fig. 19 is an enlarged portion of the U.S. Coast and Geodetic chart of 1883.

[d] Again, with objective awareness that the defining conditions and criteria for hurricanes have varied widely over history, see the Explanatory Comments preceding table 2. Cf. also David M. Ludlum's *Early American Hurricanes, 1492–1870,* pp. 131–132.

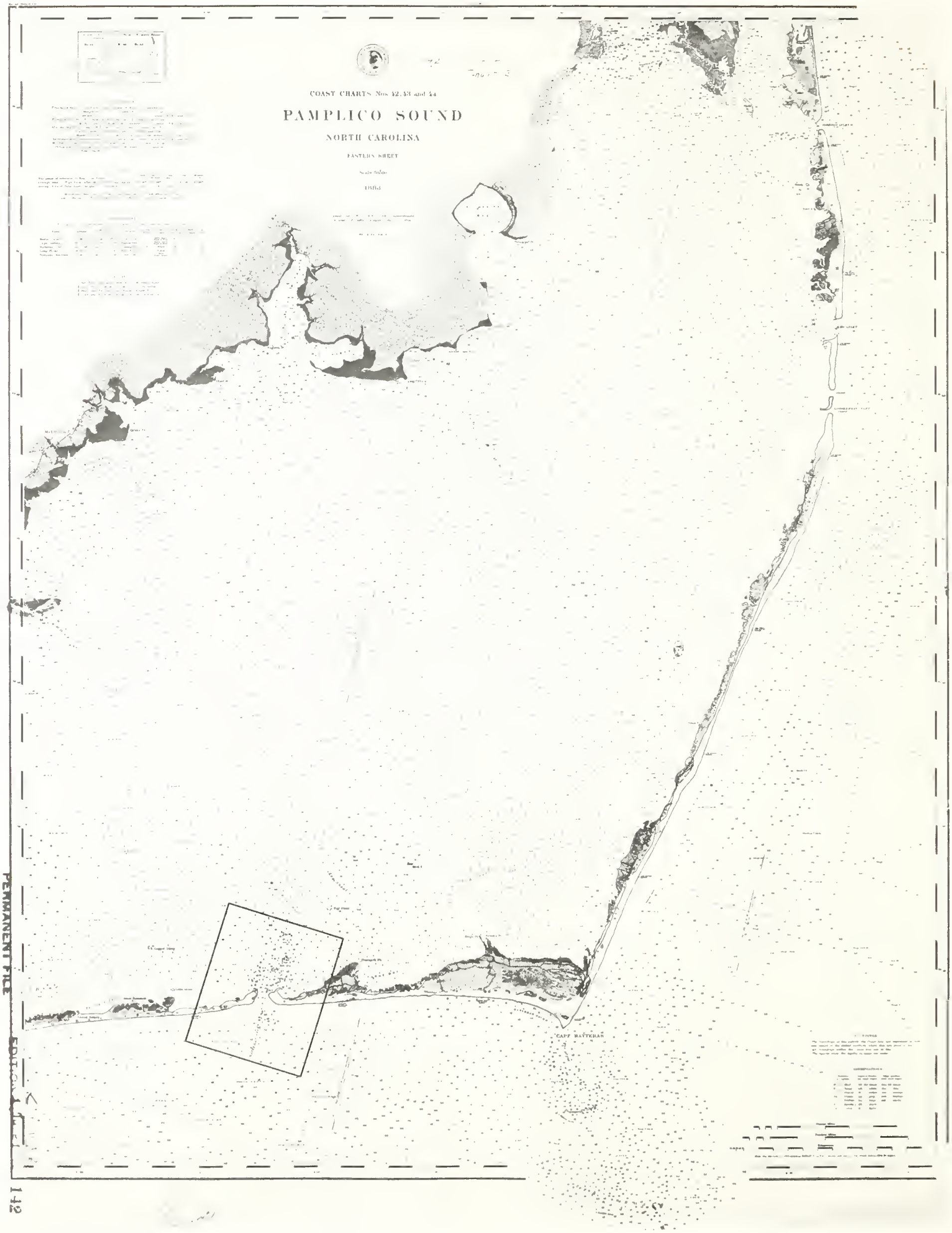
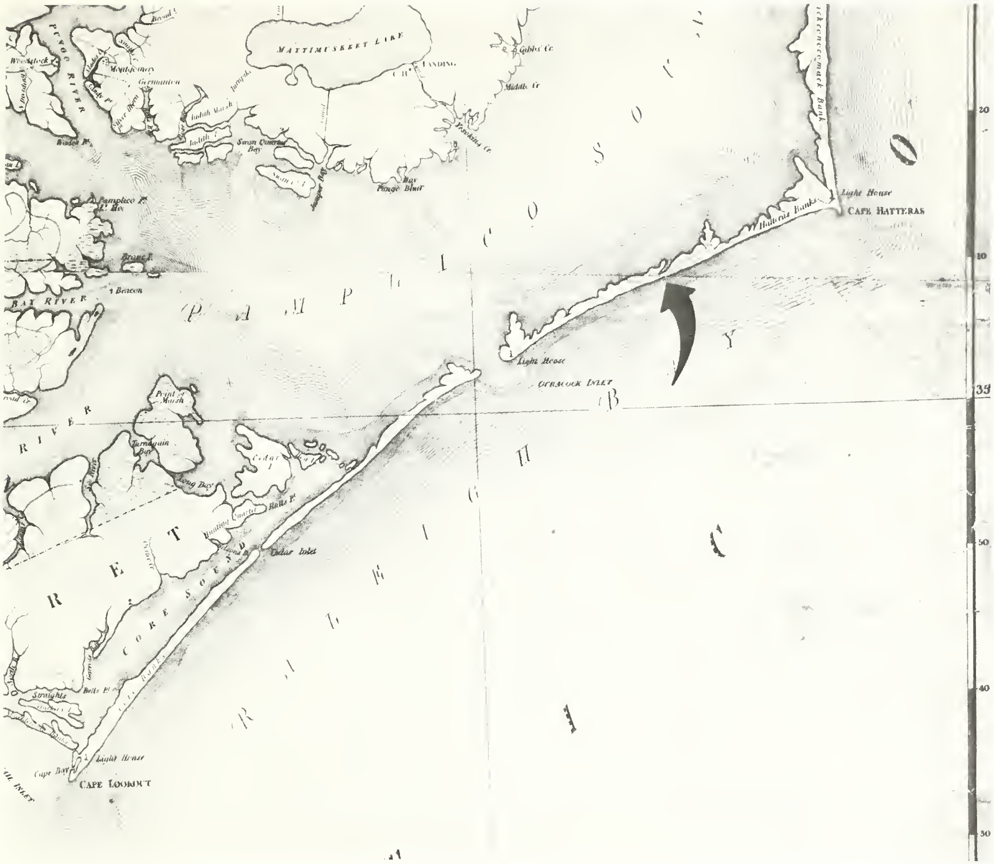


FIGURE 17.—Coast and Geodetic Survey Chart No. 142 (ed. 1) of Pamplico Sound (now known as Pamlico Sound), N.C., published in 1883. The small boxed area indicates the location of the present Hatteras Inlet, enlarged in much greater detail in figure 19.



Courtesy of Library of Congress

FIGURE 18.—Enlarged portion of a "New Map of the State of North Carolina" drawn by Brazier and MacRae in 1833. At this time, although Ocracock (Ocracoke) Inlet is clearly present, there was no breach in the Outer Banks at the present location (indicated by the curved arrow) of Hatteras Inlet. Compare with figure 19.

As acknowledged in various historical reference sources,[41, 42] Hatteras Inlet had, through this single formative process of Nature occurring a decade and a half earlier, achieved a tactical significance which would enable it to play a definite role in the Civil War. With ready access to the open sea provided for privateers and blockade runners through this inlet, Pamplico Sound became an integral part of a network of inland waterways maintained by the South to transport supplies to the Confederate Army. These waterways, in turn, formed a connecting artery of communication which made possible a considerable flow of needed supplies through Virginia, North Carolina, and other States of the South in almost complete defiance of the Union naval blockade.

Toward the end of August 1861, the Union forces were in need of a bold maneuver to counteract the inglorious defeat suffered at Bull Run some 5 weeks earlier. In an active planning stage was the first major offensive by the Federal Navy in the Civil War. Hatteras Inlet became a key element in a coordinated plan to invade this

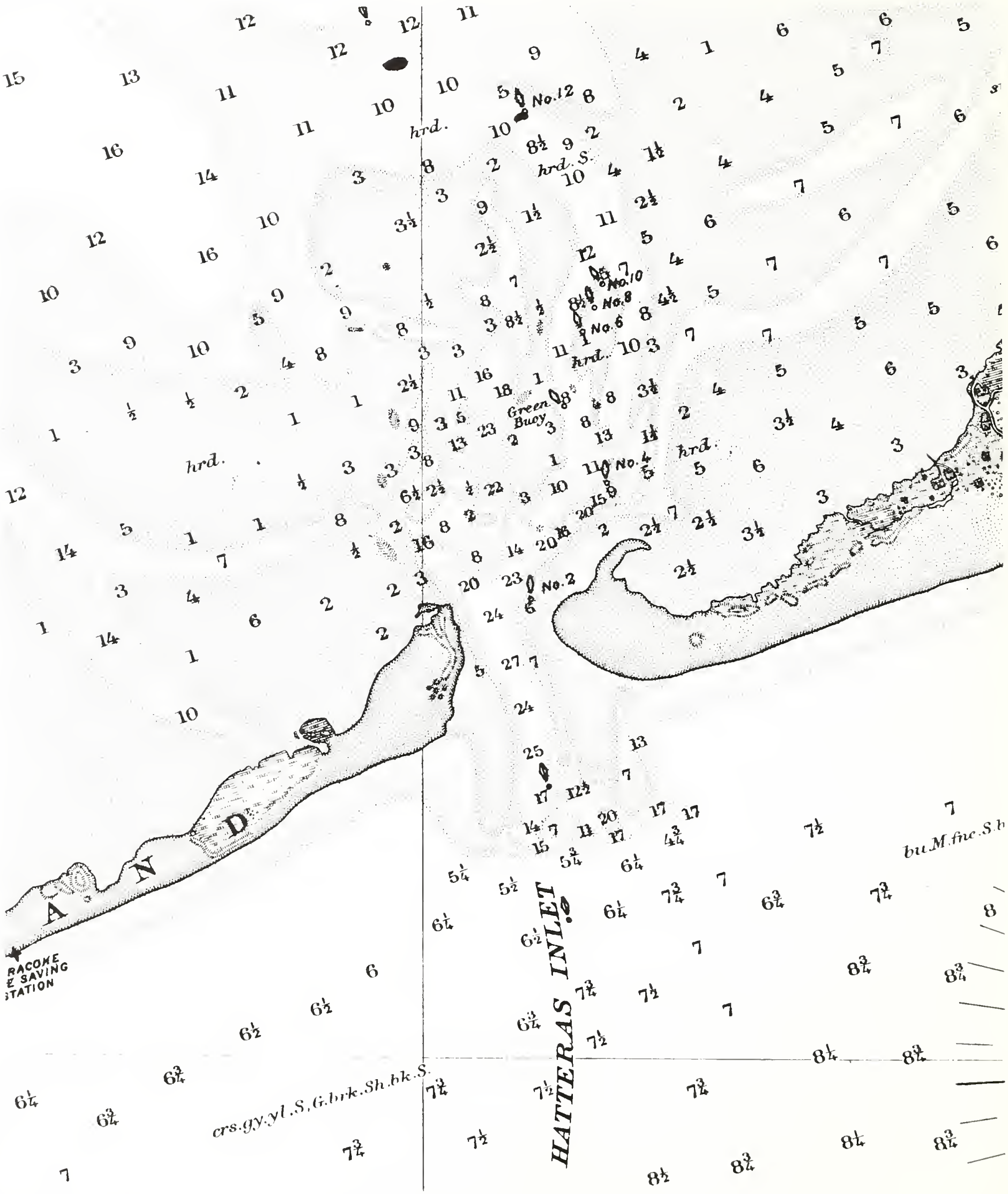


FIGURE 19.—Enlarged section of C&GS Chart No. 142, ed. No. 1 (fig. 17), showing the hydrography of Hatteras Inlet in 1883. Breaching of the barrier spit was caused by the combination of strong *offshore* winds and severe backwash flooding from Pamlico Sound on September 7–8, 1846, accompanying perigean spring tides.

Southern center of commerce by both land and sea. This decision by Northern planners had been reinforced from a strategic standpoint through information provided by the captains of several Union brigs which, earlier in the war, had been captured by the Confederate forces. Imprisoned near Hatteras Inlet, and subsequently escaping through the assistance of privateers, they had confirmed to the Northern forces the existence of the new Hatteras access channel, and reported that as many as 100 blockade runners were escaping through it each month.

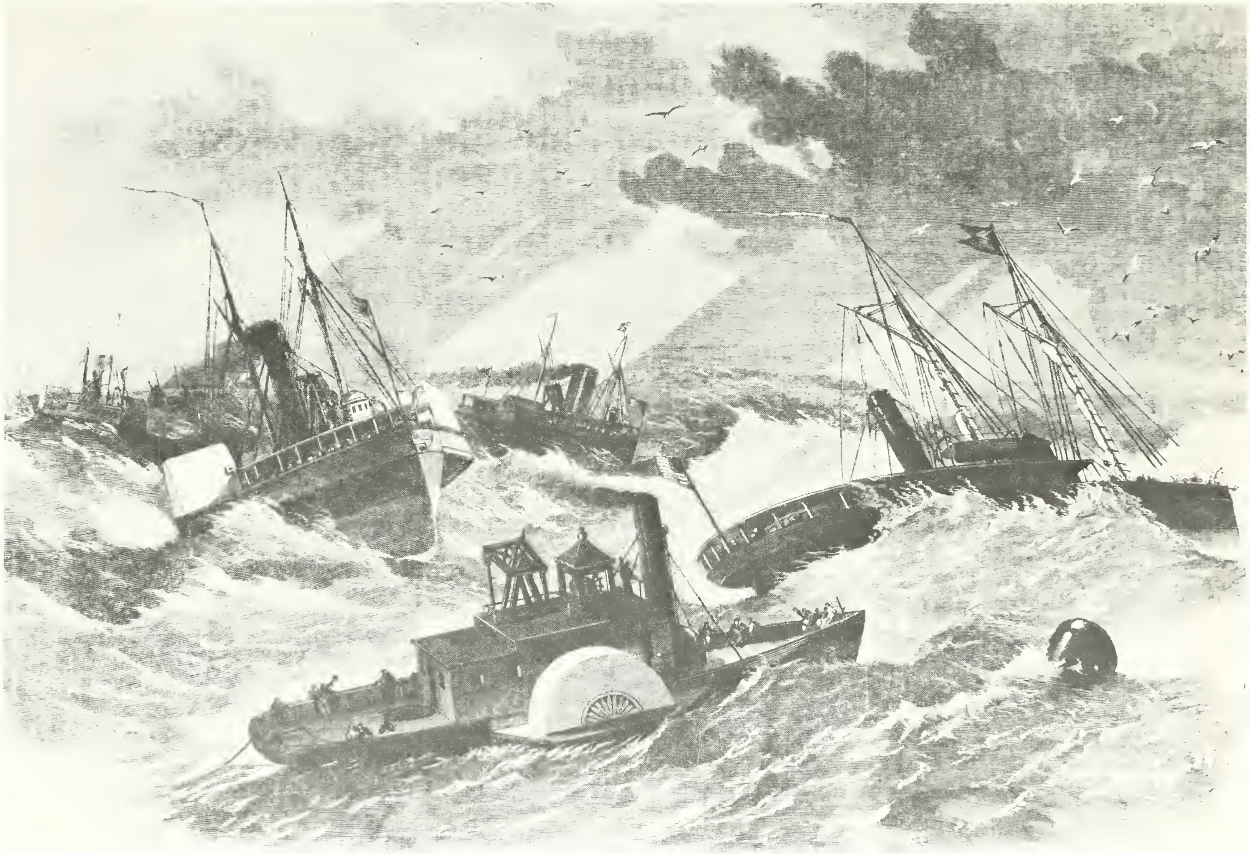
The Federal Navy Department concluded that a landing of troops from the sea on the beach near Hatteras Inlet, followed by a penetration of this inlet by ships to secure the two key forts which guarded it, was a move demanding the highest priority and worthy of the first major naval expedition into Confederate waters.

On Monday, August 26, 1861, the Union fleet set sail from Hampton Roads, Va., under the command of Flag Officer Silas H. Stringham. Troops were landed on shore, as planned, although under very adverse conditions of sea and weather. On August 28, the screw steamer *Monticello,* of 655 tons, drawing 12 ft of water and commanded by John P. Gilliss, tortuously warped into Hatteras Inlet.[43] Through the combined efforts of the fleet and land forces, and the expedient access provided by this inlet, Fort Hatteras, Fort Clark, and the waters of Pamplico Sound were secured by the Northern forces (fig. 20).

This daring entry into the shoal-infested waters of Hatteras Inlet, subject to continuous fire from Southern guns, provided a strong moral victory for the Northern forces. The immediate consequence of the capture of these Confederate forts also gave the North a strong base of operations in Southern waters and a supply depot for their blockading vessels. In securing the principal means of ingress to Pamplico Sound, the North had blocked a tactical lifeline vital to the war efforts of the Confederacy. The perigean spring tide which had, in conjunction with strong winds, created Hatteras Inlet, also made possible an event of considerable importance to the Civil War in the subsequent passage of the Burnside Expedition through this inlet (fig. 21), leading to the Battle of Roanoke Island on January 22–26, 1862.

Courtesy of The Mariners Museum, Newport News, Va.

FIGURE 20.—Vessels of the Union Navy which engaged in the bombardment and capture of Forts Hatteras and Clark in the Hatteras Campaign of 1861. The screw steamer *Monticello* (12-ft draft) which, under strong enemy fire, negotiated the new passage formed by tidal breaching in 1846 and reconnoitered the tactical situation confronting the Union Fleet, is pictured at the extreme right.



From *The Illustrated London News*, February 22, 1862, p. 187
Courtesy of The Mariners Museum, Newport News, Va.

FIGURE 21.—The new Hatteras Inlet, created by the combination of strong surface winds acting upon raised perigean spring tides, played several very important roles in the Civil War. By permitting the ships of the Burnside Expedition ready access to Southern ports, this inlet was a significant factor in the Union victory at the Battle of Roanoke Island on January 22–26, 1862. Here the *Picket* is shown leading the ships of the Burnside Expedition over Hatteras Bar.

Chapter 3.

The Practical, Economic, and Ecological Aspects of Perigean Spring Tides

In addition to the previously demonstrated potential for coastal flooding, many outstanding examples exist in which the production of perigean spring tides or their accompanying phenomena (such as strong tidal currents) has exerted a prominent influence upon projects in coastal engineering, shoreline reclamation, seawall or groin construction, and other functions, activities, or events of a technological nature. In the historical development and continuing application of both marine and maritime technology, in particular, as well as in various phases of intracoastal and harbor navigation, numerous circumstances have arisen in which the occurrence of perigean spring tides has exerted a special impact. Typical of such an historical tidal influence upon engineering projects was the complete destruction of Guglielmo Marconi's experimental transatlantic radio tower by the combination of a windstorm and perigean spring tide in 1915. This incident occurred as the result of erosion and undermining of the tower by tidal flooding at Cape Hatteras, N.C., on April 4 of this year (see table 1, chapter 1).

Although the role of these tides may have been obscured in the details attendant upon a particular activity—or the tides may have affected only a partial phase thereof—their practical contribution to the ultimate success or failure of the activity can only be described as of major significance. Among the wide range of available examples, a representative few will suffice, and these are given below.

As in all previous instances cited of relationships dependent upon the existence of perigean spring tides, it must be remembered that the astronomical forces responsible for their production are worldwide in scope. Accordingly, although the present work deals geographically with the influence of perigean spring tides in North America, the addition of a few appropriate examples to retain these tides in their proper global perspective is desirable, and will serve to emphasize their far-reaching importance. Such examples of international nature included among the following may readily be extended by analogy to the coastal waters of North America.

The Effects of Extremely Low Waters

The same augmentation of astronomical tide-raising forces which, at times of perigee-syzygy, produces above-average high tides is responsible—in the low-water stages approximately 4–8 hours preceding and following—for the production of tides which are exceptionally low. In the first case, enhanced tractive forces amass additional quantities of water near the sublunar point on the surface of the Earth (and its antipodal position) to create the increased high waters of perigean spring tides. At the same time, these increased forces draw additional quantities of water from source regions along a great circle approximately 90° from the common meridian of the first two positions. All points on this second great circle are subject to low tides. Because of the rotation of the Earth, these exceptionally high and low waters alternate, some 4–8 hours apart, at the same location during appropriate portions of the tidal cycle.

Dangers of Explosive Decompression in Submarine Environments

The building of bridges across bays, inlets, or tidewater estuaries and rivers connecting to the sea is an activity much affected by such possible alternations of extreme high and extreme low waters, and as such constitutes an area of extreme practical importance in connection with perigean spring tides. In the construction of large bridges, supported by piers whose foundations extend deep into the soil beneath and along the water channel in order to reach bedrock, an engineering procedure is used which is particularly sensitive to tidal changes.

In these projects, a device known as a pneumatic caisson is customarily employed to provide a pressurized atmospheric environment in which bridge construction workers, familiarly called "sandhogs," can work at necessary depths below the waterline without being flooded out by infiltration of water through the soil and into the open bottom of the caisson. The pressure of the water is exerted equally in all directions, and increases directly with depth according to the hydrostatic formula $P_d - P_s = \rho g \Delta d$, where P_s and P_d are the existing pressures at the surface of the water and at any depth "d" below the surface; "ρ" is the density of the water; "g" is the acceleration of gravity; and Δd is the change in depth involved. Since hydrostatic pressure is a function principally of "d", an identical pressure exists at any uniform depth in the water, as well as throughout any water-saturated earth materials situated at this same depth. Thus, as a simple example, an increase of but 16 in. in the height of the water overlying a point (easily possible in the case of perigean spring tides) results in an increase in hydrostatic pressure of 0.58lb/in^2 at all levels beneath. Even this comparatively small rise in water level thus represents an increase in hydrostatic pressure amounting to nearly 8.5 times that of the value of standard atmospheric pressure (0.068 lb/in^2). It is evident that such an increase (or decrease) in hydrostatic pressure is possible through a corresponding rise or fall in any estuarine water level which is subject to the action of a strong tidal influence.

To compensate for the increased hydrostatic pressure caused by additional amounts of overlying water (and to prevent water from flooding into the caisson) the workmen must breathe air which is compressed in excess of the standard atmospheric pressure by an amount proportional to the depth of the caisson. At a depth of 30 ft, the water pressure has increased to 13 lb/in^2, equivalent to a pressure 191.2 times that of the atmosphere. The atmospheric pressure within the caisson must, therefore, be increased to allow for the extra pressure produced by a rise in water level at times of ordinary high tides and requires a still greater increment, of the magnitude indicated above, to offset the additional height of perigean spring tides.

Aside from the ever-present danger of a physiological syndrome described as the "bends" produced by too rapid depressurization (decompression) of the workmen's breathing air (with consequent excruciatingly painful release of inert nitrogen gas bubbles into the bloodstream), another mechanical hazard exists which relates to the operation of the caisson itself. This is the possibility of "blowouts," or violent reductions of air pressure in the caisson caused by an improper seal and the sudden escape of the air contained therein to the surrounding environment. The open bottom of the caisson must at all times be kept immersed in the underlying soil to provide such an air seal.

Ordinarily, the buoyancy provided to the caisson by the contained air is balanced by the weight of the caisson. (The hydrostatic pressure of the overlying water to which the caisson is subject at any depth is noneffective in this regard since it is exerted equally in all directions.) However, should the hydrostatic pressure undergo sudden fluctuations due to marked changes in tide level, and be uncompensated by corresponding adjustments in caisson air pressure, bubbles of air may escape beneath the bottom edge of the caisson and ensuing erosion of the soil may break the air seal. An overpressurized and overbuoyant caisson may lift free from the bottom and tilt hazardously, or possibly float toward the surface.[1] As compressed air escapes from the caisson and is replaced by water, buoyancy is reduced and the caisson plunges downward again under its own weight, embedding itself in the mud. Since caissons, like the pontoons used to float bridge beams into place, also are buoyed into position on the tides, yet another possibility exists for a mishap resulting from marked tidal variation at times of perigee springs.

Such an accident happened during the construction of the Firth of Forth Bridge, in Scotland, in consequence of a perigean spring tide associated with a perigee-syzygy alignment of January 1, 1885 (at 5:00 a.m. Greenwich-meridian time, with a separation between perigee and syzygy of —13 hours). As is usual in the case of perigean spring tides, the occurrence of an extremely high tide was followed by an extremely low tide. As a result, as the water level fell rapidly, the massive caisson being maneuvered into place for the northwest corner of the Queensferry pier dropped too suddenly and imbedded itself deep in the mud. Construction of this great bridge was delayed for 10 months since, despite extensive engineering efforts, the caisson could not be freed from the bottom until October 19, 1885.[2]

In SCUBA diving operations by NOAA, small adjustments in scheduled underwater activity and decompression times are now made to permit adequate periods of decompression for divers operating beneath the increased depths (or incrementally changing depths) associated with perigean spring tides.

Ship Grounding

Ship groundings and strandings likewise may be affected by the unusually low water accompanying perigean spring tides. Although ships ordinarily do not enter or leave ports during low water, in coastwise traffic they often cruise just offshore where shoals and sandbars exist—especially at the mouths of bays and outside entrance channels. In such locations, unless proper precautions are taken, an active possibility exists for unexpectedly running aground subject to the exceptionally low-water conditions associated with the minimum stages of perigean spring tides. The danger is amplified by the strong ebb currents also present around these times. Unquestionably, a considerable number of ship strandings have occurred throughout American history which are attributable to such circumstances. Representative instances of ship groundings occurring almost exactly at the times of perigean spring tides, and which are, therefore, at least suspect as to their probable or contributing cause, are given in part II, chapter 8.

The special significance of perigean spring tides for modern supertankers and other deep-draft vessels will be considered in this same chapter.

It would be a somewhat fatuous effort to attempt to isolate those cases in which the existence of perigean spring tides might be held to be totally responsible for the grounding of ships, because often so many other attendant and possibly contributory causes (such as fog, navigator's error, mechanical failure, etc.) exist at the times of such strandings. However, the inclusion, in chapter 8, of some previous cases in which ships are definitely known to have stranded around the times of perigean spring tides will serve to point up the special dangers both for nonpowered, deep-keeled sailing vessels and ships which, through their very ponderous nature or deep-draft design, are of cumbersome maneuverability.

Whether, in the cases documented, a navigational or piloting error may have existed, coincidentally—whether a possible overlooking of updated nautical chart information may have occurred—or an adverse condition of weather or other cause may have contributed—the fact remains that the extreme low waters and strong currents known to be present in each case claimed their ultimate toll where the grounding otherwise might not have happened. These accidents obviously took place at times and locations where, had not low-water tidal conditions prevailed which were more severe than those ordinarily anticipated, the shipmasters involved never would have dreamed of running their ships aground.

It must be emphasized again that extreme perigean spring tides do not occur often enough in any one year that their influence becomes anything like a controlling one in ship groundings. Certainly, there is no intention, in presenting this factual record, to imply that ship groundings occur only at perigean spring tides or subject only to the conditions occurring around these times. Of the extremely large number of strandings which have occurred along the 86,000 mi of American coastline during the past 300 years, those mentioned are but an insignificant sample. However, should even one stranding have been caused, or be caused in the future, by a lack of awareness of this particular tidal phenomenon, it is a matter of concern to maritime commerce.[a] Because of a potential loss of life, or the vessel and its cargo, a knowledge of the inherent dangers becomes vitally important, particularly in an era of increasingly larger supertankers and other deep-draft vessels.

An interesting historical example illustrating a side effect of the extremely low waters associated with perigean spring tides is contained in the facsimile (page 42) of an article from the *New York Times* of February 10, 1895, relating to the considerable difficulty in loading and offloading cargo from a ship at dock due to the sharply inclined gangplank made necessary under such conditions. These circumstances still continue today in connection with automatic loading ramps or conveyor belts, and are of special consequence where the daily tidal range is exceptionally high, such as at Eastport, Me.

The Effects of Accelerated Currents

As will be described in greater detail in part II, chapter 8, a corollary phenomenon resulting from the perigee-syzygy relationship is an increase in the velocity of horizontal (tidally induced) water currents. This is directly related to the enhanced vertical rise and fall in water level produced by perigean spring tides. Such strengthened currents pose a special problem because of their retarding influences (when opposed to the direction of a vessel's motion) on the headway of small, slow-speed, and cumbersomely towed craft, such as barges. Through their accelerating or deflecting influences (when moving in the same direction as, or across the course of an underway craft) they likewise impair navigational control and, in all cases, may engender a threat to the grounding of ves-

[a] An analysis of U.S. Coast Guard statistics covering ship groundings over a period of 10 years reveals a total of 892 casualties to commercial vessels in which the cause was reported as "a water depth less than expected."

sels, large or small. They also strongly influence marine engineering operations which necessitate work at or below the waterline.

Impact Upon Marine Engineering Projects

Typical examples of this kind exist in the laying of foundations, cofferdams, and caisson supports for the piers of the large bridges which cross estuaries, bays, or inlets affected by tidal waters. A noteworthy example of the special problems presented by perigean spring tides during such a construction project is illustrated in the difficulties encountered during the building of the Britannia (Railroad) Bridge across the Menai Straits between Anglesey and Caernarvonshire Counties in northern Wales, Great Britain. Here the daily range of the tides varies from 2.6 to 24.3 ft, even at ordinary spring tides. The same increased gravitational forces responsible for this large daily rise and fall in water level become the basis for a further strongly activated current flow accompanying (but not a function of) the increased range of perigean spring tides.

On June 20, 1849, this tube-type railroad bridge was ready for the installation of its first span. The span was floated into place on pontoons, secured by lines to a giant capstan on shore. But the builders had not allowed for the tremendous forces involved in the fast-moving stream associated with perigean spring tides on this date (perigee-syzygy at 9:30 a.m. Greenwich-meridian time, with a separation between components of −9 hours). The current caught the pontoons, and the entire span was in imminent danger of being torn away from the flailing capstan. Only the prompt and spontaneous action of the viewing bystanders, who applied their combined strength to the restraining lines, prevented this bridge tube from floating out to sea.[3]

Dangers to Navigation and Docking

The effects of augmented tidal current flow around the time of perigee-syzygy are also evidenced in active dangers to navigation. It is here important to emphasize that the intensity of tidal currents is *not* necessarily directly related to the magnitude of the local tidal range. It will be seen in part II, chapter 7, that almost universally at low-latitude—and at certain mid-latitude stations along the east coast of the United States—as well as in the Gulf of Mexico, the tidal ranges are very small. In general, these limited tidal ranges will not support extensive coastal flooding where strong onshore winds prevail at the same time as perigean spring tides. (Although coastal flooding *may* occur in these special areas in the case of tropical hurricanes.)

Even in these low latitudes, however, tidal currents run strongly and swiftly subject to the same increase in gravitational forces responsible for the heightened perigean spring tides. Current-produced groundings of ships are common, for example, in the near-shore waters of both Florida and the Gulf coast.

Since the accompanying purely horizontal movement of water involves both a time-related inertial buildup and frictional drag different from these same factors associated with tides, the occurrence of the peak of tidal currents can either precede or follow the peak of perigean spring tides by several days. Periods of ebb currents usually last longer than periods of flood currents. As will be seen on page 98, the times of ebb and flood tidal currents often differ considerably with respect to the times of high and low tidal waters.

A typical example of an ocean liner breaking its moorings due to the strength of currents associated with perigean spring tides is given in the following excerpt from the *New York Times* of August 6, 1925:

"The strong flood tide in the North River last night caught the stern of the White Star liner *Olympic* at Pier 59 as the passengers were starting to go down the gangways with such force that the bow rope parted with a loud report and the ship slid back about 13 feet. No one was hurt. [The] captain who had given a whistle to make fast had to direct towboats again to push the big liner back into her former position."

The Influence of Improvements in Navigation Aids

Alternate possibilities have been cited above, both of strandings in the extraordinary shallow waters associated with the low-water stage of perigean spring tides, and of ships drifting ashore or aground subject to the strong currents accompanying these tides. The preponderance of such cases which occur in an early period of American history is, of course, the result of several factors:

(1) The common use, in these early times, of square-rigged ships which, because of their unwieldiness, were incapable of working readily against the wind; subject to strong onshore winds, these square-rigged vessels were often helpless against being driven into shallow waters and aground by the force of the wind.

(2) The subsequent development, in an evolutionary process, of fore-and-aft rigged vessels such as schooners and ketches—and the combined forms represented by barks, barkentines, brigs, and brigantines—involving sig-

nificant refinements in hull and sail design; these vessels were capable of beating against the wind, and this improved maneuverability made them less liable to being driven aground on bars or reefs, or ashore.

(3) The innovation of steam-driven vessels provided the necessary power to make sea room even in the face of adverse conditions of wind and current and thus reduce the possibility of grounding. (Although, even today, diesel-driven but ponderous and only slowly maneuverable supertankers may be forced aground by strong tidal currents.)

(4) The invention of echo-sounding devices provided navigators with a means of securing expedient, advance knowledge of approaching shoals, and submerged bars or reefs.

(5) When a vessel is subject to the influences of strong tidal currents at night, or under conditions of fog or impaired atmospheric visibility, the availability of modern shipborne radar reduces the danger of collision with other vessels, manmade structures, or natural features above the waterline.

The Optimum Dispersal of Engineering Demolition Products

Seymour Narrows, B.C., is a narrow strait, approximately 2.4 km (1.5 mi) in length, which lies on the eastern side of Vancouver Island in that portion of the shipping route from Vancouver to Alaska known as the Inland Passage. Through this passage, barely 660–1,100 m (2,200–3,600 ft) wide, and flowing between Maud Island on the east and Wilfred Point on the west, are some of the swiftest currents in the world. Even at neap tides, the usual surface velocity is some 14.8 km/h (8 kt) while, at the times of ordinary spring tides, the velocity increases to 18.5–22.2 km/h (10–12 kt), making normal handling of a ship very difficult against the current flow. At times of perigean spring tides, the flow of water is accelerated even more, and becomes a real hazard to the maneuvering of ships.

Compounding the navigation problems, from the very earliest days of sail between Vancouver and Alaska until the year 1958, there existed, nearly centrally within this passage, a very distinct hazard to shipping known as Ripple Rock. Oriented in a generally north-south direction, and a little closer to the western shore of the passage, this rock originally constituted a hogback-shaped, underwater obstruction whose two peaks rose to within 2.74 m (9 ft) and 6.10 m (20 ft), respectively, of the sea surface at mean low water. Because of this proximity to the surface, the submerged formations created both turbulence and whirlpools in the presence of strong currents, rendering passage extremely dangerous to smaller craft and a matter of close concern to larger vessels.

The presence of this rock had been known ever since the voyage of Captain George Vancouver in HMS *Discovery* in the year 1786, and is recorded in his journal. The first reported major ship disaster attributed to this rock involved the U.S. Navy ship *Saranac,* a 1,484-ton paddlewheel steamer which struck the rock on June 15, 1875, and became a total loss. Subsequently, and before the rock was destroyed in 1958, some 25 large vessels and several times as many smaller vessels collided with the rock, with damage ranging from partial to total loss, and at a cost of 114 lives. Included among these ship losses was the stranding of the U.S. cable ship *Burnside,* which occasioned a formal memorandum from the American to the Canadian Government recommending, on the strength of the cumulative record of disasters, the elimination of this hazard to navigation.

Technical studies were made in the years 1921 and 1931, and the first attempt at removing the rock was begun in 1942 as part of the war effort in connection with military shipping to Alaska. However, the extremely strong currents present in the passage prevented attempts to destroy the rock which were made both in this year and in 1945. These currents tore away, or caused excessive vibration in, the equipment and facilities used in an attempt to bore into the rock and to set explosive charges from a barge anchored above the obstruction.

Such preliminary tests revealed the impracticability of either drilling holes or retaining a position in the vicinity of the rock for any extended period of time because of the very high current velocities attained even at ordinary spring tides. Similar attempts to work from a barge moored to two strong steel cables running from one side of the passage to the other and anchored to heavy bolts secured in the rocks ashore also met with failure as the cables pulled loose under the intense strains to which they were subjected by the forces of the currents upon the barge. Finally, it was determined that a procedure for drilling into the rock from below by means of a shore-based access shaft and horizontal tunnel connecting to two further vertical approach shafts extending upward to the individual parts of the rock would be necessary.[4]

Such a project was inaugurated late in the year 1955 and the drilling work was completed early in 1958. The time chosen for the explosion of the charges imbedded in the rock pinnacles was April 5, 1958, at 9:31 a.m., Pacific standard time (P.s.t.). The reasoning behind this choice of time is a factor of direct importance to the pres-

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ent discussion. In order to obtain the highest current velocities possible and to ensure a quick dispersal of the explosion products, a favorable compromise in circumstances was selected. This included both extremely low tides to permit increased rock dispersal (rather than lifting a huge mass of overlying water), and a strong ebb-tide to carry the detonation products northward and thus avoid possible wave damage from the blast at docks to the south.

The compromise plan involved the optimum use of several specific tide and current factors close to the time of the explosion. These were predetermined, and the project scheduling was ostensibly adjusted to achieve a balance of the most favorable tidal conditions as well as appropriate weather and other operational factors. The tidally contributing factors were:

(1) A condition following, within some 26 hours, the strongest ebb current predicted for Seymour Narrows during the entire year. This current of 26.5 km/h (14.3 kt) was predicted for 0805 P.s.t. on April 4, 1958. At 0846 on April 5, the predicted current was still 26.1 km/h (14.1 kt). Its strong northerly set acted to carry the wave front propagated from the blast, as well as the waterborne products of the explosion, in a direction away from the nearest port facilities to the south.

Allowing for phase- and parallax-ages, the time chosen for detonation was 41 hours after a perigee-syzygy situation whose mean epoch occurred on April 3 at 1622 P.s.t., with a separation between perigee and syzygy of only −7 hours.

The only other 26.1-km/h (14.1 kt) ebb current in the year was predicted for 2022 P.s.t. on October 13, 1958. This followed by 29 hours, and was similarly associated with, a perigee-syzygy situation having a mean epoch of 1526 P.s.t. on October 12, with a perigee-syzygy separation of +5 hours. The relationship between these astronomical and perigean spring tidal circumstances in producing the highest current velocities of the year is clearly established.

This strong current situation was combined with:

(2) The selection of the first *early morning* tide of the year predicted for Canoe Pass, Seymour Narrows, which, at its low stage, was only 1.8 ft above the standard datum plane for the area. (Chosen timewise for its convenience in connection with the operational aspects of the explosion, this low-water level was also a feature particularly sought after in the project; with a very shallow depth of water overlying the rock, a more effective dispersal of the products of the explosion would be possible.)

A previous, somewhat lower tide (1.6 ft) on January 6 (aided by the Earth's proximity to perihelion) occurred at 2116 P.s.t. But this was a nighttime extreme low water, unsuited to the project—as were those associated with similar lunisolar alignments in the next following perigee-syzygy series, October 14–November 12–December 11, averaging 7 months later. The only other lower tides in the year also followed after the April 5 date, and formed a part of the same perigee-syzygy series, 1.0 ft at 0900 on May 4, 0.9 ft at 0846 on June 2, and 1.6 ft at 0831 on July 1.

Finally, to the above conditions was added:

(3) *One* of the highest tides, although not actually the highest tide, of the year. The time chosen for the explosion followed a higher high water of 15.3 ft at 0401 on April 6, with an immediately preceding lower high water of 13.9 ft at 1648 on April 5. The combination of these above-average high and low waters provided a greater hydrostatic head and a resulting hydraulic action contributing to a more efficient flushing of the navigation passage after the detonation. The mean higher high water at this location is 14.3 ft; the mean lower low water is 4.4 ft.

The principal tidal advantage sought for this project obviously related to the strong current flow. The somewhat less-than-maximum high- and low-water conditions utilized, compared with the annual extremes, represented a compromise between the various requirements.

Although the tides in the Inland Passage are of a mixed and highly complex nature, extremely sensitive to solar and lunar declinational influences, and not as sharply responsive to the perigee-syzygy effect as are those on the northeast coast of North America, tidal currents in the channel obviously are subject to this latter effect.

The example given is illustrative of yet another case where perigean spring tides have been used for a practical purpose and with successful results. This largest non-nuclear explosion on historic record was safely detonated at a propitious time, and the hazardous obstruction to navigation represented by Ripple Rock was removed to the great benefit of intracoastal navigation in this area.

Ecological Influences of Perigean Spring Tides

Numerous of the physical, chemical, and biological properties of inshore waters which form a part of bays, harbors, and inlets, and estuaries discharging thereto, are especially subject to change as the result of both the extremely high and extremely low waters produced at the time of perigean spring tides. These changes, in turn, may have a pronounced impact on the ecology of the estuarine environments contiguous to these coastal water bodies. Representative effects upon various of these parameters as the result of the greater rise and fall of the tides, and the intrusion of seawater to greater distances into the tidewater zone (and especially into regimes which normally consist of freshwater) around the time of perigee-syzygy will now be considered.

Variations In Salinity

Because of (1) the continuous (and sometimes flood-level) discharge of freshwater from coastal rivers into estuaries, and its possible retention therein by a backup of unusually high tides: (2) occasional very heavy rains combined with very low tides; (3) inshore intrusion of seawater as the result of unusually high tides; and (4) the evaporation of water in the shallow capture basins of tidelands and wetlands, estuarine regions are especially vulnerable to significant changes in salt content, or salinity. All of the foregoing conditions may occur in direct consequence of perigean spring tides. These changes may seriously affect the marine inhabitants of such inshore waters. Through associated changes in the density and specific gravity of seawater, salinity is also of consequence in altering its relative buoyancy. This factor, in turn, may influence the depth to which marine life forms (including eggs and larvae) sink—sometimes out of their life-sustaining environments.

In this same consideration of factors conducive to the preservation and development of desirable forms of marine life, various types of marine animals used for human consumption have been shown to be reduced in size and maturation in habitats of lesser salinity. Fish respiration is easier in saltwater than in freshwater, and greater schools of fish are usually found in waters of increased salinity. On the other hand, decreased salinities may support the existence of marine shipworms such as *Teredo navalis.*

From a marine biological standpoint, the zoo-plankton-phytoplankton relationship is an inverse one; where minute marine animals are reduced in numbers by low salinity, marine plants which often serve as their food source may proportionately increase to the point of forming a dense, navigation-fouling mass, particularly where nutritional salts are available from sewerage waste materials. Water contamination inevitably results.

Thus, specifically, a class of algae known to marine biologists as diatoms may either serve beneficially as good grazing (herbivorous) marine animals, or may destructively foul estuaries by their too prolific development. A key factor in the growth of many species of diatoms is the establishment of an appropriate rate of osmosis between the body fluids of these basic organisms and the water in which these organisms live. It is known that the salinity of seawater plays a significant role in providing the necessary partial pressure for osmosis to occur, and in the continued preservation of this osmotic relationship.

Some species of (stenohaline) marine animals—usually, but not always, residents of the deep sea—are extremely sensitive to changes in salinity. Other (euryhaline) animals display a wide tolerance to saline variations, or can make necessary adjustments thereto—but not under extreme conditions.

A phenomenon known as *entrainment* in estuarine waters is also a function of changing relative salinity with depth. Entrainment is that process by which the freshwater outpouring from streams into an estuary, being less dense than saltwater, overrides the latter, and moves offshore through the estuary at a level near the water surface. At the same time, in compensation, more dense saltwater moves into the estuary from the ocean to form the bottom waters of the estuary, the so-called "saltwater wedge." The direction of currents may thus differ by as much as 180° between the surface and bottom water in the estuary.

A characteristic accompaniment of the estuarine environment is the production of "saltflats," "marshlands," and "tidelands" by the tidally induced inflow and outflow of saltwater. The biological regimen is usually quite closely controlled by the saltwater, in which, among plants, only marshgrasses will grow. Extreme high tides such as those produced at times of perigee springs, with consequent isolation of water in shallow pools, can cause evaporation basins to develop. The local salinity increases, marine life is choked out, and waterfowl and seashore wildlife are affected. Pollution and noxious odors also result from the decaying grass and fauna.

Marine life is ordinarily protected against any quick change in salinity in a closed-basin environment by the high latent heat of evaporation, which also means that an existing low-saline water mixture does not suddenly chill as evaporation occurs from its surface. However, such marine life is not protected against marked increases in the relative salt concentration of the water such as may occur by sudden intrusion in the case of windblown and flood-producing perigean spring tides.

Increased salinity of seawater may also variously act to: (1) exert a greater corrosive influence on ship hulls (with an accompanying increase in the production of rust); (2) discourage the growth of green algae in coastal waterways along docks, piles, and piers; and (3) provide a source of incrustations and vegetation-killing salt deposits wherever evaporation occurs in shallow marshland pools. In this latter respect, increased salinity may also have an effect on the use of estuarine water husbanded in the tidewater zone for irrigation projects.

Variations in Carbon Dioxide Content

The presence of carbon dioxide in seawater is vital to both marine flora and fauna because of the necessity for these marine lifeforms to absorb quantities of carbon into their systems and, through synthesis, to convert carbon, oxygen, and hydrogen into carbohydrates. In the case of marine flora, this is accomplished through the process of photosynthesis; in the case of marine fauna, the action is accomplished through respiration and metabolism. The necessary source of carbon in each case exists in the abundant carbon dioxide found in seawater.

On the other hand, the presence of plantlife, absorbing certain limited quantities of carbon dioxide and leaving the seawater slightly alkaline, favors the synthesization of carbonates by hard-shell animals dependent upon the building up of their shells by absorption of these carbonates. A balanced ecobiological condition is thus maintained which is very sensitive to changes in carbon dioxide content of the seawater. The stability of the carbon dioxide content is a necessary aspect in the existence of many forms of marine life, and the existence of an exact carbon dioxide-oxygen balance is extremely important to all marine life forms.

The quantities of carbon dioxide dissolved in seawater can be increased as the result of strong evaporation, or by an increase in salinity. In an action opposite to that of most gases dissolved in a water solution, the amount of carbon dioxide absorbed by the water also increases as the temperature *decreases*. Any of these properties of the volume of seawater associated with, or resulting from, the incursion of perigean spring tides far up into the tidewater area may produce the variations noted, with consequent effects on the ecobiology.

Variations in Water Temperature

Many forms of marine life are extremely sensitive to temperature variations, are incapable of adjusting rapidly to marked changes in the temperature of the water environment, and may expire if these temperatures are altered suddenly or if temperature extremes are imposed upon their habitats. Increased water temperature, through the resultant expansion of the water, is associated with reduced densities which can cause water to rise through a colder surrounding environment. As the temperature rises, the capacity of the water for absorbing oxygen from the air also decreases, starving the fish of needed oxygen. The production of temperature extremes is not frequent in the case of the encroachment of perigean spring tides from the open sea. However, the production of their associated strong currents may change the temperature of the surface water considerably by horizontal advection of warm water, or replacement of warm surface water by cold water from below if upwelling or overturning and mixing, produced by density differences, should occur simultaneously with the intensified flood or ebb currents.

As will be seen in chapter 7 of part II, the dynamic impact of the unusually high water levels and strong currents associated with perigean spring tides is a powerful one when these tides are accompanied by strong, persistent, onshore winds. Often resulting in major structural damage along the coastline, the physical effects of these two concurrent factors are also of importance in connection with: (1) the diffusion or turbulent dispersion of pollutant wastes as a function of concentration (density); (2) the resulting relative buoyancy within the water environment; and (3) the presence or absence of vertical currents.

Estuarine pollutants of comparatively high density with respect to the water will normally sink to the bottom because of their weight. Here they can become trapped in the cold and dense water below a thermocline surface (possibly accompanying a "saltwater wedge") in the estuary in the same general manner that smog pollution is held down beneath a temperature inversion in the atmosphere—but with different effects. A temperature inversion in the atmosphere (warm air above cold) is a stable condition which prevents mixing and supports pollution of the atmosphere by ground smoke. Conversely, a situation of warm water above cold (while also a stable one) holds heavy pollutants near the floor of estuaries where they are least bothersome.

However, the presence of a sharp temperature gradient between cold water near the surface and warm water below a thermocline can result in turbulent mixing and lifting of the pollutants to the surface. The altered thermal conditions produced by the strong influx of cold water in a wind-driven perigean spring tide can give rise to this situation.

The Effect Upon Grunion Runs

Along the southern coast of California, from southern Baja California to Monterey Bay, a familiar source of nighttime sport fishing on the beaches (and, to a limited extent, commercial fishing from near-shore boats) is the member of the silverside family (resembling smelt) known popularly as grunion. These fish, which are gifted with a very remarkable "biological clock," are found nowhere else in the world.

During their regular spawning season, from February through August of each year, thousands of these fish ride the crests of incoming waves which occur less than an hour after the maximum high-water stage of ordinary spring tides (i.e., tides associated with either the new or full phase of the Moon). The fish are washed ashore by the breaking waves. As each female fish is carried well up onto the beach, she lays her eggs in the sand just below the maximum high watermark reached in the current cycle of high tides. Here the eggs are simultaneously fertilized by the males.[5]

The eggs remain in the soft, moist sand during the period of time required for hatching—which corresponds almost exactly with the one-half lunar month required for the Moon to reach the opposite phase of syzygy (i.e., from new moon to full moon or the reverse). If the eggs were laid even a short time after the crest of higher high water, they might easily be reached and gouged out by the higher high water of very nearly the same height occurring slightly more than 24 hours thereafter, or by the next succeeding lower high water some 12 hours later—in either case far too early in their 2-week hatching cycle. If the eggs were laid too soon, before the crest of higher high water, they might be gouged out again at the peak of this HHW stage. The same principle applies to the necessity for spawning at the highest of the two daily high tides, since if eggs were laid at lower high water, they would be washed out to sea again during the higher high water of the same 24-hour day. The exact moment selected for spawning is, therefore, very critical, and the grunion obviously possess some undetermined sensory ability to isolate an interval of time occurring immediately following the downward turn of an appropriately selected spring high tide.

During the peak of the grunion spawning season, March through June, spring tides produced at full moon may be either slightly higher or slightly lower than those produced at new moon. The particular syzygy configuration associated with the highest tides depends upon which of these two lunisolar alignments agrees most closely in time with that of perigee. Thus, the highest tidal peak in any one month occurs at full moon on those occasions when the time of perigee is closest to this lunar phrase, and at new moon when perigee lies nearest to this alternate position of syzygy.

The perigee position (representing the closest proximity of the Moon to the Earth) provides an extra gravitational force lifting each such set of reinforced spring tides to an even greater height. As a further consequence, the uplift of this one spring tide in each monthly pair is greater the smaller is the separation in time (and hence the closer is the geometrical alignment) between perigee and syzygy, culminating in the condition known as perigee-syzygy.

In addition, the greater of these two monthly peaks alternates between new moon and full moon once in each 6.0–6.5 to 7.0–7.5 months (see chapter 6). This maximum tidal peak also rotates with respect to the seasons during successive years as a function of the net forward motion of perigee in the lunar orbit (see chapter 4). A complete reversal from a maximum tidal peak at full moon to a maximum peak at new moon during a given month of the year takes place in a period equal to one-half the time (8.85 years) required for perigee, subject to solar perturbations, to rotate once around its orbit. (Compare, for example, in west coast tide tables the greater of the two higher high water (nighttime) syzygian tides at San Diego, Calif. at *full moon* during the spring of 1976 and those at *new moon* during the spring of 1972, approximately one-half perigean cycle earlier.)

As a general rule, grunion tend to avoid the higher of the two syzygian tides in each lunar month in favor of either the immediately preceding or following smaller spring tide. Were the fish to deposit their eggs at the higher peak of the two spring tide maxima in each lunation, it would mean the lapse of a full month before the tide reaches the height of the eggs once again.

Laying of the eggs at the time of the lesser maximum in each cycle ensures the certainty that the following higher maximum at syzygy some 2 weeks later will reach them again and wash them back out to sea. Ten days to 2 weeks is the normal hatching period for grunion eggs and represents the optimum time at which they should be returned to the sea for continuing existence. For various reasons, any extension of this period reduces their probability for survival.

Similarly, readily granting the ability of grunion to sense, in advance, the differences between growing tidal heights, these fish would be expected to avoid egg laying at the peaks of perigean spring tides. This is because it would be 6 or 7 months before sufficiently high tides once again reached the spawning grounds to return the eggs to the sea (and possibly not then—depending upon the relative heights of the two tides).

In fact, among the limited available data tabulating grunion runs by actual dates, it has not been possible to find such runs occurring at the maximum crests of perigean spring tides. However, they do occur in the lesser high waters of syzygies preceding or following a peak perigean spring tide—or in the declining stage of this tide, as happened at Ocean Beach, Calif., on February 8, 1978.

Miscellaneous Environmental Influences

An historic ancillary effect of perigean spring tides which is no longer of any consequence was the influence of these tides in causing the penetration of saltwater up tidal rivers alternately for several days, sufficient either to cause the breakup, or prevent the formation and cutting of, blocks of ice for storage and sale at ice houses alongside the river. However, this same influence continues today as then in the action of such tides in bringing saltwater far up coastal rivers to points well beyond the normal tidewater mark. Numerous related effects may result from the intrusion of these tongues of saltwater variously into agricultural, sports fishing, or ecobiological environments unsuited to receive them. Adverse effects also may result from the overflowing of river banks not built to withstand the accompanying tidal increase in water level—or floods produced by blocking of the downstream hydrological runoff resulting from any coincident, excessively heavy precipitation. Some of these effects are described below:

1. Because the presence of salt in water lowers the freezing point of the solution compared with that of freshwater, the incursion of such saltwater tongues is very effective in preventing the freezing of a river at points upstream which would normally be covered with ice at comparable temperatures. For example, under such hard-freeze conditions, portions of the Hudson River, usually icebound, would remain open to navigation for the same reason that the saltwater of New York Harbor remains free of ice cover.

2. Subject to the influence of perigean spring tides, the subsequent breakup of a sheet of river ice already formed can also create a navigational hazard as the ice floes are propelled by much stronger surface currents associated with perigean spring tides. A danger of ship collision with these ice floes occurs as falling tides and their outgoing (ebb) currents carry the ice blocks downstream and the return (flood) currents created by rising tides carry them partially back, in the respective portions of each tidal cycle. Ordinarily, such ice floes require several days and successive tidal cycles to make the downstream journey leading to the point of outflow to the open sea. The collision of ships with these ice floes is possible anywhere en route.

3. In navigational channels and at dockside facilities located above the normal tidewater mark, the increase in water level resulting from perigean spring tides is also combined with an increased buoyancy caused by the saltwater intrusion and its greater density in comparison with freshwater. As a result, any vessel will ride proportionately higher in the water. This fact may add to the steepness of the more conventional run-out angles between gangplanks or cargo conveyor belts and piers (see pp. 42, 54, arts. *N.Y. Times* 2/10/1895, 10/24/1953). Waterline or load-line readings likewise must be obtained from the saltwater Plimsoll marks rather than the freshwater Plimsoll marks.

4. The relative freedom from pollution of an estuary into which waste products and sewage are regularly discharged is, in part, a function of the amount of flushing which occurs within the estuary subject to the action of successive high and low tides. As a consequence of the higher HHW, lower LLW, and stronger currents associated with a perigean spring tide, the flushing action is increased, resulting in an improved dispersal of pollutant wastes.

5. A sample instance of the practical impact of perigean spring tides upon fishing activities involved the occurrence of this type of tide on July 19, 1974. The case reported related to the failure of a small commercial fishing enterprise to find any schools of flounder in their customary deepwater haunts in Chesapeake Bay on this particular day—threatening to negate the entire day's catch. (Flounder customarily favor the sidewalls or ledges of deeper channels and prefer sandy, rather than muddy, estuarine bottoms.) The fish were finally accidentally discovered, moving upstream in the shallower and quieter waters close to the extreme outer banks of the bay, a location which they chose in order to avoid fighting their way against the unusually strong downstream currents in the deeper parts of the channel, caused by the perigean spring tide.

6. Vacationers are also apt to find beaches on which they are accustomed to sunbathe—and which are generally dry and sufficiently broad above the waterline to accommodate crowds even at high tides—completely covered with water and unusable during times of increased perigean spring tides.

Recapitulation of the Practical Influences of Perigean Spring Tides

A fairly representative listing of the practical and economic effects of perigean spring tides, both adverse and beneficial, is summarized below. These influences are grouped by category, with prototype examples being given in all cases where substantiating evidence is available. In addition, to provide proper balance, there are included a select number of instances of the contributions made to scientific research in related geophysical projects by the enhanced gravitational forces associated with perigee-syzygy.

Influences of Perigean Spring Tides for Which Substantiating Evidence Is Available

(Representative examples, by date and locality, are given in parentheses following the description of each influence which has been corroborated in one or more instances to date. In those cases preceded by the letter "W," the effects noted are made possible only when the astronomical high and low waters, amplified by the coincidence of lunar perigee and syzygy, are also accompanied by strong, persistent, onshore (or offshore) winds, respectively. As the winds increase in velocity, the indicated effects are increased in proportion. In those cases preceded by a "T," the intensified astronomical high or low waters alone are sufficient to produce the observed effects.)

1. Increased Tidal Rise, at High Water
   a. Adverse Effects

W (1) Coastal flooding, with damage to beach homes and condominiums, shoreline structures, wharves, docks, and marinas; occurrence of shore and beach erosion, wave gouging, scouring of berms, scarps, and foreshore; breakover and undercutting of seawalls, bulkheads, and waterfront roadways; inundation of saltflats, drainage swamps, and tidewater marshes; destruction of marine fauna and flora in the intertidal zone; ravaging of waterfowl refuges, coastal wildlife sanctuaries, and national seashore parks; damage to inshore fishing grounds, and to oyster, mussel, and other hardshell beds; disturbance of the natural ecological balance. (More than 100 representative instances of severe tidal flooding occurring along both the Atlantic and Pacific coasts of North America over a period of 341 years are listed in tables 1–2.)

T (2) Elevation of high-water level above that of sewerage outfalls, causing impairment and improper distribution of pollution runoff (Pacifica, Calif., December 20, 1972.)

T (3) Retardation of hydrological runoff (resulting from intense rainfall, snowmelt, freshets, etc.) to the sea, thereby increasing the coastal flooding potential from these sources; this blocking of runoff at high water adds further to the flooding impact of landfalling hurricanes (including typhoons, tropical cyclones, or baguios), and both tropical and extratropical coastal storms, if perigean spring tides occur coincidentally therewith (Boston, Mass., March 21, 1936.)

W (4) Buoyant uplifting of small craft (or their mooring buoys) to the limits of their anchor lines. This may result in a dragging of anchors and/or shearing of mooring cables, with loosing and dispersal of the small craft to the forces of wind and sea. (Severe threat at Avalon Harbor, Catalina Island, Calif., January 8, 1974.)

W (5) Subject to the exceptional tide rise, a possible buoyant uplifting of sailboats docked in boathouses to the point of impact of nonretractable mastheads with the roof overhang.
(Avalon Harbor, Catalina Island, Calif., January 8, 1974.)

W (6) With the same marked rise in water level, a potential inability for the mastheads of tall, lightly loaded (and nonballasted) vessels to pass beneath the nonraisable or nonrotable trusses of bridges spanning bays, sounds, straits, or estuaries.

T (7) Inundation and concealment of bars, sunken wrecks, rocks, or pinnacles usually exposed under high tide conditions and at ordinary spring tides but, with the high waters of perigean spring tides, posing a potential navigational hazard. (Execution Rocks, Long Island Sound, N.Y.—numerous occasions.)

(8) In implanting the pneumatic-type caissons used in the construction of piers for bridges across estuaries, coastal embayments, etc., an increase of only 16 inches in the depth of the overlying, or the sat-

urated interstitial ground waters requires an increase of approximately 8.5 times the atmospheric pressure within the caisson in order to prevent water infiltration. A definite danger exists for serious seepage into, or flooding of, the caisson if the ambient pressure in the caisson is not increased to compensate for the additional hydrostatic head of water associated with perigean spring tides. T
(See also the opposite, occasionally encountered "blowouts" under 2a(4).)

(9) A small but quantitatively significant adjustment must be made in decompression and/or bottom times of divers engaged in activities which entail a close observance of the operational parameters of depth and time. Because of the increased hydrostatic pressure to which the divers have been subjected at all depths, the extra height of perigean spring tides (and the sensible variation in the column of overlying water from low to high tide) may necessitate going to a new diving schedule. T
(Considered in NOAA/MUST diving programs since the perigean spring tide of January 8, 1974.)

(10) Extraneous influences may be induced in Earth-tide measurements. These take the form of tilting or deformation of the Earth's crust (together with possible short-period subsidence effects) caused by transient but appreciably increased tidal loading along the coast. Leveling observations conducted around the times of these extraordinarily high tides, as well as deflection of the vertical in astronomic observations, and systematic gravity anomaly measurements, all may be affected thereby. T
(See part II, chapter 8.)

b. Beneficial Effects

(1) Possibility for navigation over otherwise too shallow and impassable bars, reefs, or other underwater features. (Release of frigate *Trumbull* from the mouth of the Connecticut River, August 11, 1779; Second Siege of Charleston, S.C., March 20, 1780; Battle of Port Royal Sound, S.C., November 5, 1861.) T

(2) Breaching of new inlets or channels, permitting ship passage through previously impassable offshore barrier spits. W
(Hatteras Inlet, N.C., September 8, 1846.)

(3) Increased flushing of bays, harbors, and estuaries as the result of the greater water-intermixing and mass-transporting capabilities of perigean spring tides and their associated stronger tidal currents; this causes a greater dispersal of the effluent pollutants which are discharged into these water bodies, and an optimum diffusion and attenuation of water contaminants. T

(4) Provision of necessary test conditions for pursuit of quantitative investigations in the field of physical oceanography and for enhancement of knowledge of the ocean environment; e.g., the observed destabilization, destratification, and decay influences produced in internal waves by excessively high tidal waters. T
(*Meteor* Expedition, April 13–16, 1937; *Pioneer* Expedition, June 12, 1964.)

(5) A means for possible updating and refinement of classical geophysical experiments, such as:

(a) Empirical checks on the mass of the Moon (although this method as originally used is not very accurate) (William Ferrell, Boston Harbor, 1871).

(b) Determination of the rigidity of the Earth from varying attraction of the Moon. T
(Albert A. Michelson, Yerkes Observatory, University of Chicago, March 1914.)

(c) Isohaline undulations in the deep-water layer (the "Moon-waves of the Gullmar fiord" directly related to extensive herring catches along the Scandinavian coasts).
(Otto Pettersson, Denmark, 1912.)

2. Decreased Low Tides, at Low Water (the effects thereof are intensified where the existing astronomical low tides are accompanied by strong, persistent, *offshore* winds).

   a. Adverse Effects

      W (1) Causing supertankers and other deep-draft vessels (especially those engaged in coastwise traffic) to strand as the result of unusual and unexpectedly low water in shoals and shallows, or because of sharply reduced water levels over bars and reefs; poses an associated danger of oilspills and other environmental pollution.

      T (2) Causing boats at dockside or moored to buoys in estuaries which are normally subject to a large tidal range to settle aground on their keels—necessitating a special scaffolding or "mattress" at some locations to prevent them from capsizing. (A frequent occurrence in the tidewaters of the Bay of Fundy.)

      T (3) Requirement for unusual and difficult adjustments in gangplanks, offloading belts, etc., at low tide (and high water.) (New York Harbor, February 9, 1895; Jersey City, N.J., October 23, 1953.)

      T (4) A potential hazard from "blowouts" in connection with pneumatic caissons used in construction of bridge piers across tidal estuaries, etc., if suitable atmospheric pressure adjustments are not made for the lower hydrostatic pressure resulting from the lesser weight of overlying water at extreme low tide.

   b. Beneficial Effects

      T (1) Exposing of portions of the seafloor ordinarily covered by water—a boon to marine biologists, marine archeologists, shipwreck hunters, beachcombers, etc. (Pacifica, Calif., December 20, 1972; Dunwich, Suffolk, England, January 11, 1974.)

      T (2) Opportunity to undertake repairs to fixed marine structures at low levels not usually permitted, but now accessible above the waterline.

3. Strong Tidal Currents

   a. Adverse Effects

      T (1) Difficulty in maneuvering heavily loaded cargo ships, tankers, and barges, or tugs and ferries; danger of collision with bridge supports, pier pilings, and docking facilities, as well as intercollision with other boats; accompanying threat of environmental pollution by oilspills, etc.

      T (2) Increased transport of bottom sands and sediment; shifting of bottom features and alteration of hydrography through silting, deposition, or scouring.

      T (3) Accelerated diffusion of oilspills, waste products, sludge, and other contaminants, and possible shoreline pollution before appropriate protective measures can be taken.

      T (4) Danger to boats, both channel-moored and underway—and to bridge supports, piers, moles, and shoreline bulkheads, from rapidly drifting ice floes ("harbor masters.") (New York Harbor, February 9, 1895.)

      T (5) Difficulty in emplacing caissons, in floating bridge trusses into place, and in consummating other marine engineering or diving operations subject to the strong current flow.

      T (6) Maneuvering difficulties experienced in deepwater diving operations involving lightweight one- and two-man submersibles; perigee-syzygy as a possible contributing cause of "turbidity currents." (NOAA two-man submersible operations in Oceanographer Canyon, July 17, 1974; encounter with turbidity current.)

      T (7) Formation of "tide rips" (as distinguished from "rip currents") offshore. In the formative process, the progress of ocean waves is slowed down and their height is increased by encounter with an oppositely flowing current of considerable strength (4–5 kt). The wave slopes are steepened, and the formerly smaller waves develop into larger, breaking waves of short wavelength, offering considerable resistance to, and retarding the passage of, small vessels. The strengthened tidal currents associated with perigean spring tides may provide the adverse currents producing such "tide rips."

(Tide rip and internal wave observed aboard US&GS Ship *Pioneer* in Andaman Sea area off northwest coast of Sumatra on June 12, 1964.)

3. a. (8) Disturbance of the thermohaline balance usually present in estuaries. When an inmoving tidal current is large in comparison with the outgoing flow resulting from discharge of rivers, etc., an increased mixing of fresh- and saltwater occurs. This action destroys the stabilizing effect T of an existing wedge of heavier saltwater along the bottom, tapering upstream, with overlying freshwater flowing downstream. Such mixing can both overturn the stabilizing entrapment of cold bottom water—bringing this colder water to the surface—and eliminate the existing thermocline.

(9) Production of dangerous navigational currents due to hydraulic gradients formed within basins interconnected by a narrow channel or strait, where the exceptionally T high perigean spring tides occur at different times at opposite ends of the channel (e.g., in Deception Pass, Puget Sound, Wash., or in Seymour Narrows, east of Vancouver Island, B.C.).

(10) Creation of extremely intense erosional currents by the "resurgent" action of perigean spring tides as the high water breaks over offshore spits and low barrier islands. The accumulating head of water is trapped in lagoons, shallow bays, or sounds and, as the external tide lowers, attempts to discharge again to the sea through existing narrow channels or by resurgence over the barrier spit. Extenn- T sive scouring and breaching may result. Ocean-floor erosion may also occur in the shallow waters of the Continental Shelf, due to accelerated ocean currents associated with a condition of perigee-syzygy. It is noteworthy that the entirely wind-attributed destruction of a U.S. Air Force radar (Texas) tower 60 mi off the coast from New York City on January 15, 1961, nearly coincided with a very close perigee-syzygy situation of January 16 (17.5^h e.s.t.).

b. Beneficial Effects

(1) Strong currents associated with perigean spring tides may act as a deterrent to the formation of sheet ice in extremely T frigid weather. This function will tend to keep narrows and other navigational channels open and clear of solid ice when such passage (for transportation of fuel and supplies, etc.) is essential.

(2) These same currents can also cause solid shields of ice, formed during protracted cold spells and impairing all navigation, T to break up mechanically before more favorable weather arrives which is sufficiently warm to produce thawing. (Documented case, February 13, 1687. See table 1, Ludlum[18] p. 25.)

(3) A contribution to oceanographic and geophysical knowledge (e.g., more precise quantitative investigations of the electrical T current flow generated by the motion of strong tidal currents through the Earth's magnetic field).

4. Other Potentially Correlatable Geophysical Influences

Establishment of a possible gravitational relationship between the astronomical conditions responsible for oceanic perigean spring tides and any similar reinforcement of atmospheric tides—e.g., a conceivable correlation between the astronomical condition of perigee-syzygy and the property of dynamic convergence in atmospheric pressure systems producing low-pressure centers. Only such low-pressure cells possess sufficiently tight pressure gradients to produce the strong, persistent, onshore winds necessary for active coastal flooding in connection with perigean spring tides.

A tantalizing but statistically uncertain zone of agreement exists between these two phenomena throughout the more than 100 years of joint tidal and meteoro- T logical records intercompared in the present study.

(From the meteorological viewpoint, an analytic study made in the Meteorological Statistics Group, ERL, involving

62 years of record, shows an apparent positive correlation between U.S. precipitation—generally associated with low-pressure centers—and the times of lunar syzygy.)

A significant and increasing number of scientific investigations are now being undertaken into the possible interrelationships between various gravitational force influences acting throughout the solar system and terrestrial weather, earthquake production, and other geophysical phenomena. All of these studies involve tidally induced effects, in one form or another.

(Cf. *Nature*, May 28, 1966, p. 893; *Nature*, November 10, 1972, p. 91; *Irish Astronomical Journal*, December 1972, p. 298; *Journal of Geophysical Research*, November 10, 1973, p. 7709; *New Scientist*, January 10, 1974, p. 54, *Geophysical Journal of the Royal Astronomical Society*, May 1976, p. 245; also part II. chapter 8.)

Chapter 4.

Survey of the Scientific Literature on Perigean Spring Tides

In tracing the earliest beginnings of knowledge concerning perigean spring tides, it is noteworthy that a clear awareness of the concepts of lunar perigee and syzygy (conjunction or new moon, and opposition or full moon)—as well as the possibility of their near-coincidence in time—existed even in a very ancient period of astronomy. Such empirically deduced lunar orbital positions have been documented in various primary reference sources, as noted below.

Historical Origin of the Concepts of Perigee-Syzygy and Perigean Spring (Perigee-Spring) Tides

The Greek astronomer Hipparchus (c. 125 B.C.), from observations of the apparent angular size of the Moon as a measure of its distance from the Earth, possessed a basic knowledge of the variability of the lunar distance during the course of the month. From these same data, he was also aware of the effect of the near-coincidence between perigee and syzygy in bringing the Moon closer to the Earth, as described in part II, chapters 4–5 of the present volume. This closer distance of the Moon becomes one of the causes contributing to the greater heights of perigean spring tides.

This early knowledge of changing lunar distances is clearly brought out, for example, in Johann Kepler's *Astronomia Nova* (1609),[1] in his discussion of Hipparchus' rudimentary determination of the distance of the Moon, specified in units of the Earth's semidiameter. The considerably closer distance of the Moon (expressed as a smaller number of Earth-radii) at the position of perigee-syzygy compared with that at apogee, and at the Moon's mean distance is indicated in the words:

"Hoc itaque pacto Hipparchus (ut habes Cap. VIII, Opt. page 313) Lunae distantiam in syzygiis perigaeam exhibuit 71 semidiametrorum Terrae, apogaeam 83, mediocrem 77, igitur eccentricitatem 6, hoc est, qualium radius orbis 100000, talem eccentricitatem 7792, quod est fere duplum ejus, quod ex variata diametro superius erat inventum."

Consistent etymological, if somewhat inadequate scientific descriptions of perigee and syzygy also appear variously in ancient Arabic, Hindu, and Greek treatises on the heavenly bodies. References to these specific terms are contained, for example, in such classic works as Μεγάλη σύνταξιϛ τῆϛ Αστρονομίαϛ (Great System of Astronomy) or *Almagest* of Claudius Ptolemaeus, Alexandrian astronomer (c. A.D. 100–170). The principles enumerated in this magnum opus[a] were disseminated widely in subsequent Latin translations (e.g., in *Theorica planetarum,* by Campanus of Navara, 13th century and later, Section IV, Theory of the Moon),[2] and other eclectic sources.

Mention of these same orbital configurations further occurs in several medieval lunar treatises (e.g., those of Johannes de Sacrobosco and Robert Grosseteste)—although perigee is incorrectly defined in those works which carried over the Ptolemaic theory of epicenters. Among early contributors to a knowledge of varying lunar distances and gravitational force influences as they affect the tides was Johann Kepler, German astronomer (1571–1630). With reference to the specification of lunar positions in orbit according to a system repeatedly used throughout the present volume, it was he who first established the relationships between the position of perigee and the anomalistic angle (of the Moon) in orbit. The anomalistic angle is, in this case, defined as the angular distance of the Moon from perigee.

Despite such early, a priori manifestations of astronomical knowledge, the increased gravitational forces resulting from the simultaneous occurrence of perigee-syzygy—and the effect of this concurrent astronomical alignment upon the Earth's tidal waters—did not become a matter of particular notice until, with the development of naviga-

[a] But cf., R. R. Newton, "The Authenticity of Ptolemy's . . . Data." *Q. J. R. astr. Soc.* (1973), *14,* 367–388; *15,* 7–27, 107–121.

tion and commerce, actual tide observations were made. Significantly, the discovery of the special nature of perigean spring tides took place only when the increased tide-raising influences of these coinciding lunisolar positions were observed in mid-latitude regions removed from the Mediterranean—since, in the latter regions, tidal ranges exhibited but minor daily variations. The mathematical development of tidal theory during the 18th century further substantiated the relationship between perigean spring (or perigee-spring) tides and the astronomical occurrence of perigee-syzygy.

The earliest discoverable published reference in the English language to the phenomenon of perigean spring tides and their potentially destructive capacity when associated with strong, persistent, onshore winds is a published letter of 1670 transmitted to the Royal Society of London, titled "Animadversions on Dr. [John] Wallis' Hypothesis of Tides." Dr. Wallis' "Essay About the Flux and Reflux of the Sea" had been communicated and read to the Society in 1666. After requesting a copy of this essay from Henry Oldenburg, member of the Society, Joshua Childrey, rector of Upwey, England, and an ardent observer of natural phenomena, commented on the essay in the above-mentioned letter relayed through Bishop Seth Ward, in which he refers to an earlier publication of 1653, by himself, as follows:

"There is yet another thing, which seems to have (at least) some influence on the Tydes, and to make them swell higher than else they would do, to wit the *Perigaeosis* of the Moon. And this hath been my opinion (taken up first upon the consideration of the Moons coming nearer the Earth) ever since 1652, when living at *Feversham* in *Kent* near the Sea, I found by observing the tydes, (as often I had leisure), that there might be some truth in my Conjecture; and therefore in a little Pamphlet, published in 1653, by the name of *Syzygiasticon instauratum,* I desired, that others would observe that year, whether the Spring-Tydes after those Fulls and Changes, when the Moon was in *Perigaeo* (the wind together considered), were not higher than usual. And since that time I have found several high Tydes and Inundations (though I must not say *all,*) to happen upon the Moons being in, or very near her *Perigaeum.*" [3]

In his monumental *Philosophiae naturalis principia mathematica* of 1687, Sir Isaac Newton acknowledged the effect of perigean spring tides (without designating them by name) through illustration in a practical example contained in Corollary I to Proposition XXXVII, Problem XVIII, Book III: The System of the World. The data presented in this sample problem are purely representative, using the tidal situation at Bristol, England. The analysis is based upon a previous example involving only the solar component of spring tides, in which Newton derives (Proposition XXXVI, Problem XVII) the height to which the tidal waters will rise acted on by the Sun alone (at points both directly beneath and on the opposite side of the Earth from the Sun) in excess of that at places which are 90° removed from the Sun.

[Note: In this connection, an important, but uncorrected typographical error (for "$113\frac{1}{30}$ inches" read "$11\frac{1}{30}$ inches") occurs in the numerical value given on page 479 in the 1729 edition of the *Principia* translated from the Latin by Andrew Motte, as extensively revised by Florian Cajori (1946).[4] A comparison between the 1803 edition of Motte's English-language translation ("as carefully revised and corrected by W. Davis") and the primary Latin source reveals that this error has been carried forward, both unrectified and unannotated, and despite several successive editings, for 143 years into the Cajori text.] Newton's original, true comparison (the original is in Latin) is (page 481):

"Cor. I. Since the waters attracted by the sun's force rise to the height of 1 foot and $11\frac{1}{30}$ inches, the moon's force will raise the same to the height of 8 feet and $7\frac{5}{22}$ inches; and the joint forces of both [syzygies] will raise the same to the height of $10\frac{1}{2}$ feet; and when the moon is in its perigee [perigee-syzygy] to the height of $12\frac{1}{2}$ feet, and more, especially when the wind sets the same way as the [incoming] tide." [5]

The additional effect of perigean spring tides (produced near the time of perigee-syzygy) compared with ordinary spring tides (occurring at syzygies apart from perigee) is clearly specified, and the reinforcing influence of wind action on such perigean spring tides is also indicated.

In the year 1764, the British astronomer Roger Long published a five-volume work on *Astronomy* in which, in chapters 4 and 5 of volume 2, book 4, he discusses various aspects of perigee and syzygy—and their relationship to tidal heights—at some length.

In Vol. I of the first edition of *Encyclopaedia Britannica,* published in 1771, a fundamental article by James Ferguson, Scottish astronomer and inventor of a tide log, includes the following concise statement:

"The moon goes round the earth in an elliptic orbit, and therefore she approaches nearer to the earth than her mean distance, and recedes farther from it, in every lunar month. When she is nearest, she attacks strongest, and so raises the tides most; the contrary happens when she is farthest, because of her weaker attraction. When both luminaries are in the equator, and the moon in *Perigeo,* or at her least distance from the earth, she raises the tides highest of all, especially at her conjunction and opposition; both because the equatoreal parts have the greatest centrifugal force from their describing the largest circle, and from the concurring actions of the sun and moon." [6]

John Hamilton Moore's *The New Practical Navigator,* the first U.S. edition of which was published in 1799, shows a practical seaman's knowledge of the independent effects of both perigee and syzygy and their combined effects in producing high water levels higher than those associated with common spring tides. In the light of a subsequent discussion in the present volume relating the rate of tide growth to the resulting height of the tide (chapter 8), Moore's early mention of this factor is also of interest:

"When the moon is in her *perigaeum,* or nearest approach to the earth, the tides rise higher than they do, under the same circumstances, at other times; for, according to the laws of gravitation, the moon must attract most, when she is nearest the earth. The spring-tides are greater about the time of the equinoxes, that is about the latter end of March and September, than at other times of the year; and the neap-tides are then less; because the longer diameter of the spheroid, or the two opposite floods, being then in the earth's equator, will describe a great circle of the earth; by the diurnal rotation of which those floods will move swifter, describing a great circle in the same time they used to describe a less one, parallel to the equator; and consequently the waters being thrown more forcibly against the shores, must cause them to rise higher." [7]

Finally, a statement previously quoted in connection with the navigational value of the additional heights of perigean spring tides (page 68) is given again, since it also indicates, in appropriate historical perspective, an early knowledge of the recurring cycles of perigee-syzygy alignments. The extra rise of perigean spring tides above ordinary spring tides is clearly stated:

". . . Some of these effects arise from the different distances of the moon from the earth after a period of six months, when she is in the same situation with respect to the sun; for, if she be in perigee at the time of the new moon, she will, in about six months after, be in perigee about the time of full moon. These particulars being well known, a pilot may chuse [sic] that time which will prove most convenient for conducting a ship out of any port, where there is not a sufficient depth of water on common spring-tides." [8]

18th Century Tidal Literature

During the 18th century, the astronomical origin of the tides occupied the attention of some of the foremost scientists of the period, who approached the matter largely from the standpoint of dynamic theory. Among such outstanding contributors to the theory of the tides were: Daniel Bernoulli, Swiss mathematician, author of the essay *Traité sur le flux et reflux de la mer* (1738); Colin Maclaurin, Scottish mathematician, whose essay *De causa physica fluxus et refluxus maris* (1738) also appears in his classic work *A Treatise on Fluxions* (1742); Leonhard Euler, Swiss mathematician and physicist, who wrote *Inquisitio Physica in causam fluxus ac refluxus maris* (1738); and Marquis Pierre Simon de Laplace, French astronomer and mathematician, whose monumental *Traité de mécanique céleste* published in five volumes, 1799–1825, contained much of the groundwork of tidal theory. The three essays of Bernoulli, Maclaurin, and Euler mentioned above were all submitted in a competition held by the Academy of Sciences of Paris in 1738, and all won prizes. Because of the theoretical nature of these three papers dealing with tidal forces in general, no special treatment was given therein to the dynamic origin of perigean spring tides.

The extensive multivolume work of Laplace cannot be as lightly dismissed, since the author treats so extensively all of the problems of celestial mechanics, including the complexities of lunar theory. He devotes the entire fourth book of his treatise, titled "On the Oscillation of the Sea and Atmosphere" to the subject of tides, and includes selected empirical examples of tide heights as produced by various positions of the Moon and Sun.

Laplace perhaps comes the closest, in this period of the development of tidal theory by mathematical scientists, in considering the combined tidal force effects of perigee and syzygy. For example, he compared the actual measured heights of 12 apogean tides with those of 12 perigean tides (both being observed simultaneously at one of the syzygies) and discovered that these values were in accord with existing prediction theory—discounting the considerable difference in the Moon's motion in celestial longitude between the times of apogee and perigee. (See table 21 of the present work.)

In a section titled "Du flux et du reflux de la mer" in his three-volume work on *Astronomie* (1771), the French scientist Joseph Jérome le François de Laland presents a purely descriptive account of tidal forces and actions. In this, he includes a brief quantitative summary of actual tide heights observed at Brest subject to the combined action of the Moon and Sun at syzygy, and with the Moon also at perigee, but the data are fragmentary and entirely selective.

Early 19th Century Tidal Literature

Perigean tides as well as ordinary spring tides—but not the combination of the two to yield perigean spring tides—are described by Nathaniel Bowditch, American mathematician, in the classic mariner's manual *The New American Practical Navigator,* published under his name in 10 editions from 1802 until his death in 1838, and under that of his son, Jonathan Ingersoll Bowditch, through 25 additional editions between 1838 and 1867. Since 1869, this work, redesignated *American Practical Navigator,* has been continuously revised and reissued as Publication No. 9 of the U.S. Navy Hydrographic Office (since July 10, 1962, the U.S. Naval Oceanographic Office). In his original volume Bowditch undertook to correct more than 8,000 tabular errors appearing in John Hamilton Moore's earlier work titled *The New Practical Navigator.* However, the previously quoted concept from Moore's book, outlining the special value of perigee spring tides to navigators in negotiating a passage across offshore bars, did not find its way into Bowditch's work in any form.

The 19th century also brought new investigations and contributions to tidal theory by: the Englishman Thomas Young, variously physician, physicist, and Egyptologist, superintendent of *The Nautical Almanac* and secretary of the Board of Longitude, who wrote a comprehensive article on "Tides" in the Supplement to the 4th, 5th, and 6th editions of *Encyclopaedia Britannica* (1815–1824); Sir John William Lubbock, English astronomer and mathematician, who wrote *Elementary Treatise on the Tides* (1839); William Whewell, English philosopher and mathematician, who rationalized extensively on various natural phenomena, including a "Treatise on Tides" in the *Admiralty Manual of Scientific Enquiry* (1849); Rear Admiral Robert Fitzroy, British naval officer and meteorologist, who as commander of the *Beagle* on the famous biological exploring expedition, had the opportunity of observing worldwide tides at firsthand and who, accordingly, wrote such articles as "Notice of Tidal Observations" (1861); and Sir William Thomson, 1st Baron Kelvin, British mathematician and physicist, who devised an apparatus for taking oceanographic soundings, invented a tide predictor and an harmonic analyzer, and discoursed on tides in Thomson and Tait's *Natural Philosophy* (1883). No special attention was paid by the foregoing writers to the specialized type of tide forming the subject of the present investigation.

A classic article on "Tides and Waves" was written by the British astronomer, Sir George Biddell Airy, for the *Encylopaedia Metropolitana* in 1845 and was republished in *The Encyclopedia of Astronomy* 3 years later. In this, only a general discussion is included concerning the concepts of heightened tides resulting from increased forces occurring separately (or simultaneously) at perigee and syzygy. He does recapitulate Laplace's empirical data previously mentioned, and compares some of these earlier and subsequent observations in the light of new theory.

However, this relatively scanty attention paid to perigean spring tides as summarized in the preceding three sections was soon to change its focus as the result of Nature's own intervention.

The "Saxby Tide" of October 5, 1869

The destructive effects of this particular perigean spring tide which, driven additionally by a strong onshore wind, devastated an entire section of the eastern Maritime Provinces of Canada in 1869 were extolled for many years thereafter by the local residents. An interesting, but scientifically unacceptable "prediction," which directed public attention to the special vulnerability of perigean spring tides in terms of coastal flooding preceded this particular onslaught of Nature. The individual involved in connection with this advance warning was a Lieutenant S. M. Saxby of the Royal British Navy, whose only other contribution to technical literature appears to have been the publication in 1868 and 1869, in the *Transactions of the Institution of Naval Architects,* of several engineering papers dealing with the properties of metals used in ships. However, in his naval activities, he undoubtedly also had ready access to *The Nautical Almanac* (published since 1767) and, by close scrutiny thereof, he made a bold deduction.

In November of 1868, he sent a letter to the London press warning—11 months in advance of the tidal flooding subsequently experienced—of the potential flooding dangers to be expected on October 5, 1869 from a special case of astronomical perigee-syzygy occurring near that date. This particular phenomenon, he noted, was coupled with a situation in which the Moon would simultaneously be very near to the Earth's Equator (declination $-0.6°$) and the Earth would also be approaching perihelion. In consequence of the necessarily magnified tide-raising forces and the extreme high tides that would result, he stipulated—rather too broadly and all too sensationally—

the certainty that this condition would be accompanied by definite coastal flooding.

In his prediction, he included no restriction of the flooding to lowland coastal regions nor to latitudinal and hydrographic circumstances capable of providing a sufficient ordinary tidal range to make the amplified perigean spring tides a hazard. Neither did he consider seasonal and climatological conditions at various latitudes and locations which could either contribute to, or effectively nullify, the likelihood of strong, persistent, onshore winds. He did not make use of either the exact Greenwich times of the individual components of perigee-syzygy, nor the mean time of occurrence of the combined phenomena. He further did not allow for longitudinal time differences or tidal delays caused by local hydrographic factors, phase- and parallax-ages, etc., at various locations around the globe.

Instead, he categorically stated that the morning tide of 7:00 a.m. on this date would be marked by a rise to extreme high waters. He also extrapolated the significant impact of his warning beyond the certain, astronomically predictable conditions of the tide. Through a nebulous assertion of a relationship between "atmospheric disturbances and [the position of] the moon on the equator," he also included a prediction for an atmospheric storm of exceptional severity on this same date.

On the other hand, he did not indicate that, in this particular instance of perigee-syzygy, the Moon and Sun were within —7 hours of direct alignment in longitude and, as a result (pt. II, ch. 4), the Moon would also undergo an unusually close perigee approach to the Earth (with a relatively large geocentric horizontal parallax of 61′24.0″). Astronomically, therefore, the condition was one conducive to the production of exceptionally large tide-raising forces, and would create a perigean spring tide offering a natural "setup" for wind attack. As the subsequent content of the present work will reveal, the extremely high tides resulting were, indeed, susceptible to flooding conditions in lowlying coastal regions where strong, persistent, onshore winds might occur. Albeit, the absolute necessity for such an accompanying meteorological condition (not possible to predict 11 months in advance) to occur in order to cause flooding was not even brought out in Lieutenant Saxby's communication. The significant technical portions of his letter to the press follow:

"I now beg to state with regard to 1869 at 7 a.m. October 5th, the Moon will be at the part of her orbit which is nearest to Earth. Her attraction will be therefore at its maximum force. At noon of the same day the Moon will be on the Earth's equator, a circumstance which never occurs without marked atmospheric disturbance, and at 2 p.m. of the same day lines drawn from the Earth's centre would cut the Sun and Moon in the same arc of right ascension (the Moon's attraction and the Sun's attraction will therefore be acting in the same direction) in other words the new moon will be on the Earth's equator when in perigee, and nothing more threatening can, I say, occur without miracle. The Earth it is true will not be in perihelion by some 16 or 17 seconds of semidiameter.

"With your permission I will during September next (1869) for the safety of mariners briefly remind your readers of this warning. In the meantime there will be time for the repair of unsafe sea walls, and for the circulation of this notice throughout the world." [9]

It is noteworthy that nothing at all was said in this letter concerning specific local conditions of weather on this date. The warning was predicated entirely from astronomical and tidal considerations, combined with a completely unexplained, all-pervasive atmospheric disturbance whose exact location is left unspecified.

A subsequent, even less scientific letter, sent to the Halifax, Nova Scotia, press by a local citizen, was probably motivated, as often happens, by the desire to derive publicity from the interest achieved by an original news story. There is, as a matter of record, a completely charlatanistic attempt by one Frederick Allison of Halifax, who wrote to the *Halifax Citizen* about a week before the forthcoming tidal phenomenon, predicting a heavy gale in this city between October 4–5, precisely at the same time as that of the predicted extreme tide. The forecast was based on a "theory of the Moon's attraction as applied to Meteorology" which, in the vagueness of its detail, is not deserving of further mention. Suffice it to say, as in all cases of unqualified release of sensational information, these two disclosures aroused considerable public concern.

In the light of the actual extreme coastal flooding resulting from the combination of a winter storm whose onshore winds arrived coincidentally with the close fulfillment of Saxby's prediction for augmented high tides, an air of prophetic hocus-pocus was, unfortunately, given to this case which weakened the scientific value to be derived from its occurrence.

The exact meteorological conditions existing along the eastern coast of the United States and the Maritime Provinces of Canada on October 5, 1869 are summarized in a paper on this storm and attendant tidal flooding read by D. L. Hutchinson, Canadian meteorologist, before The Canadian Institute some years later.[10] These conditions are further discussed in David M. Ludlum's *Early American Hurricanes,* 1492–1870 (in this latter connection, see also the Explanatory Comments preceding table 2).

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A partial description of the damage created by tidal flooding in this area, as presented by Hutchinson in the aforementioned paper, is as follows:

". . . On the day of the storm (Monday, Oct. 4th) the early morning was foggy, then part clouded and by 7 a.m. fine and warm, in the afternoon assumed a dull leaden colour becoming completely clouded by 5 p.m. As the afternoon advanced the wind blew in fitful angry squalls and the rising tide was noticed to be coming in unusually early. At 5 p.m. the wind had increased to a gale and rain began falling at 6 p.m. The gale continued to increase, about 8:30 p.m. it was blowing with hurricane force from S. by E. reaching its maximum velocity about 9 p.m. when the rain almost ceased. About 10 p.m. the wind began to subside shifting to S.W.

"The night is said to have been exceptionally dark with shingles, slates and other debris blown about in a most dangerous manner. When the gale was at its height (about 9 p.m.) the tide was much above any preceding mark, was rising rapidly and had an hour and half to come. In St. John harbour and along the water front the waves were coming in from the Bay of Fundy to a tremendous height dashing over every wharf along the whole harbour line, while the vessels moored at them seemed as if they must be rolled over upon the wharves by the next swell. Vessels broke away from moorings, some were driven ashore and many badly damaged.

"Buildings near the water front were flooded in lower floors, warehouses were destroyed, everywhere signs of destruction met the eye, slips, coves and beaches were filled with debris from the wreckage. . .

". . . The high tide at St. John backed up the river to such an extent that it rose upwards of three feet at Fredericton. On the St. John River near Gagetown in Sunbury County a river steamer had her upper work carried away by the gale.

"In Albert County the damage from wind and tide was excessive and at that time estimated at nearly a quarter of a million dollars.

"Westmoreland had a terrific gale and the highest tide ever known, tons of hay destroyed on the marshes, cattle drowned in great numbers, whole barns and their contents carried away, telegraph lines destroyed and the roads made impassable. From 'Tide Levels and Datum Planes in Eastern Canada' by Dr. W. Bell Dawson, it may be seen that the water level at Moncton was nearly six and a half feet above former or subsequent records.

"At Moncton the tempest and tide was most disastrous, while at Shediac, and Point Du Chene on the gulf not eighteen miles distant, no damage of any description was done.

"In the Bay of Chaleur the water was much above normal and at Dalhousie, Restigouche County, bordering on the bay, the lower portion of the town was inundated and boats used to remove property and people from the lower levels.

"At the head of the Bay of Fundy, in the Basin of Minas, in and about Cumberland, Hants, Kings and Colchester Counties, N.S., the gale was not severe, but rain fell heavily. The chief damage was caused by the tide, dykes were broken away in all directions, in some places the water was two feet above the second floor dwelling houses, many hundreds of cattle, sheep, etc., drowned, large quantities of hay destroyed, great stretches of railroad carried away and travel made impracticable in any direction. The wind itself did not do much injury, except to the fruit crop. At Windsor, N.S. wharves were damaged and churches, dwellings and business places flooded. . ." [11]

Hutchinson summarizes the meteorological conditions producing the accompanying storm and wind as follows:

"In all probability the storm was one of tropical or semi-tropical origin characterized to the southwest by extremely heavy precipitation and greatly increasing in energy as it moved towards Eastern Maine and the western portion of New Brunswick." [12]

However circumstantial the coincidence of meteorological and astronomical conditions which produced this extensive coastal flooding through the cause-and-effect relationship which is clearly beyond the scope of Lieutenant Saxby's prediction, this event was for years thereafter known among the local residents of the area as "Saxby's Tide" or "Saxby's Gale" and has also been discussed in the scientific literature of this period under this same designation.

Late 19th Century Tidal Literature

William Ferrell, American meteorologist, and a tides expert with the U.S. Coast and Geodetic Survey from 1867 to 1882, touched upon various aspects of perigean spring tides in such papers as "On the Moon's Mass as Deduced from a Discussion of the Tides of Boston Harbor," and "Tidal Researches." These were published in the annual *Report of the Superintendent of the Coast Survey* for 1870 (Appendix No. 20) and 1874 (Appendix), respectively. His "Report of Meteorological Effects on Tides," published in the same annual volume for 1871 (Appendix No. 6) is especially germane to the present monograph and includes a mention of tidal reinforcement by meteorological effects when these occur at a time of perigee-syzygy (without naming the corresponding tides as perigee springs), as follows:

". . . Sketch No. 38 contains a graphic representation of the heights of the tides and of the lunitidal intervals given by the tables and by observations, and of the effects of the winds and changes of atmospheric pressure, for the month of July, 1858. This is the time when the obliquity of the moon's orbit to the equator is greater than in any other part of the whole series, and, consequently, when the diurnal tide is the greatest. This causes the alternate heights of high and low waters to be greater and less, as represented in the sketch, near the times of the greatest declinations of the moon, the maximum of the lunar and principal part of this effect occurring two days after the greatest declination. At this time, also, the moon's perigee occurs near the time of one syzygy [sic] and its apogee near the time of the other. Hence the predominating influence of the lunar parallactic inequality over that of the solar, or half-monthly, is well represented by the sketch. At the time of the new moon and the moon's perigee these two inequalities combine and make the tides unusually large, but at the time of full moon and the moon's apogee the parallactic inequality more than counteracts the half-monthly inequality, so that when in European ports there is a second maximum, though smaller, in Boston Harbor this second maximum is entirely destroyed by the predominating effect of the lunar parallactic inequality, and the magnitude of the tides do not come up to the mean tide . . ." [13]

A basically theoretical article on "Tides" was prepared by the British astronomer Sir George Howard Darwin for the *Encyclopaedia Britannica,* 9th edition, *23* (1880), and later republished separately as "The Tides" (1898). In this article, the subject of perigean spring tides escapes any specific mention. The same lack of any particular discussion of this type of tides occurs in Volume I, "Ocean Tides and Lunar Disturbances of Gravity," in Darwin's collected *Scientific Papers* (1907).

In his prodigious five-volume work, titled *Manual of Tides* (parts 1–5, 1894–1907), Rollin Arthur Harris, then chief mathematician of the U.S. Coast and Geodetic Survey, developed a wave theory of the tides, and includes numerous individual references to perigean tides as well as to spring tides, but does not evaluate their combined effects.

In his outstanding treatise on *Hydrodynamics,* published in 1895, the English fluid dynamicist, Horace Lamb, included an analytic explanation of the retardation of the maximum effects of spring tides following times of new or full moon,[14] a phenomenon which plays an important part in the similar delay of perigean spring tides frequently observed on the east coast of the United States. (See text in re table 19.) Lamb's analysis was based upon earlier theoretical approaches to the same problem in William Thomson's and P. G. Tait's *Natural Philosophy,*[15] in G. B. Airy's encyclopedia article on "Tides and Waves," [16] and by Hermann L. F. von Helmholtz in *Lehre von den Tonemfindungen.*[17]

Other important investigations relating in whole or in part to the tides which were published in this same period include: *Hydrography and Maritime Meteorology,* by Carl Borgen (1886); *Les méthodes nouvelles de la mécanique céleste,* by Jules Henri Poincaré (1892–99); "On the Application of Harmonic Analysis to the Dynamical Theory of the Tides," by Sydney S. Hough, in *Philosophical Transactions,* A, vol. 191 (1898); *Leçons sur la théorie des marées* by Maurice Lévy (1895–98); and numerous contributions such as "On Waves," by Lord Rayleigh in *Philosophical Magazine, 1* (1876).

A new empirical approach to tidal knowledge which would include some of the quantitative aspects of perigean spring tides was to come principally at the start of the next century.

20th Century Tidal Literature

The pursuit of knowledge, like the recurring variations of the tides, seems to move in cycles. The turn of the century was marked by a very considerable increase of interest in the practical aspects of perigean spring tides, to be followed, incongruously, by an almost complete disregard thereof throughout the ensuing period of almost 50 years.

In the Bay of Fundy in Nova Scotia, and in certain other localities, the tide is of the so-called *anomalistic type* (i.e., closely related to the Moon's anomalistic period—or the time from perigee to perigee). Here, fluctuations in tidal range with the Moon's changing distance from perigee to apogee are the largest variations experienced. In such cases, even the difference in range from neap to spring tide may be of lesser consequence than that caused by the perigee-apogee variation.

The previously mentioned "Saxby Tide" represented a case of perigee occurring nearly coincidentally with syzygy, while the Moon was located at an extremely close perigee distance from the Earth. Its anomalistic effects were, accordingly, very strongly felt in the Bay of Fundy region and might very likely have generated the ensuing spark of interest in perigean spring tides. In any event, numerous Canadian Government reports relating to the survey of tides and currents in Canadian waters—especially in the years from 1902 to 1907—are replete with comparisons of extreme tidal ranges, exceptionally large current velocities, and cases of coastal flooding and damage produced at times of perigee springs. These reports were variously published by the Department of Marine Fisheries, the Department of the Naval Service, and the Royal Society of Canada.

The same topical emphasis on empirically derived data led to the development of *A Practical Manual of Tides and Waves,* by W. W. Wheeler, published in 1906.

In 1913, the causes of long-period variations in astronomical cycles—and their commensurate interrelationships—formed the basis for a lengthy article by a Danish scientist, Hans Pettersson, in *Publications de Circonstance* (published by the Counseil Permanent International pour l'Exploration de la Mer). He called upon such commensurable periodicities to explain various astronomical alignments which create the maximum possible tide-raising forces. The influence of perigean spring tides is among the topics treated. The author includes a considerable discussion of the particularly strong tide-generating force produced by the coincidence of perigee-syzygy and perihelion, especially when combined with a simultaneous positioning of the Moon on the ecliptic at either of its nodes. He also brings out the influence toward the production of extreme tides provided by an unusually close proximity of the Moon to the Earth (involving an exceptionally small perigee distance and corresponding large value of geocentric horizontal parallax which will later be described as *"proxigee"* in the present monograph). The reduced lunar distance and increased geocentric parallax are, in turn, caused by an exceedingly close perigee-syzygy alignment.

In a book titled *Houle, rides, seiches, et marées* (Swells, Ripples, Seiches, and Tides) published in 1924, Henri P.M. Bouasse of the University of Toulouse, France, discusses several empirical aspects of the heightened tides resulting from the near-coincidence of perigee and syzygy. A considerable discussion is also included relative to the maximized tidal effects produced by the occurrence of perigee-syzygy while the Sun and Moon are over the Equator, a phenomenon which the French call *la grande marée d' équinoxe.* An approximate example of this type which is cited is that occurring near March 13, 1918.

In his semipopular work *The Tides,* published in 1926, H. A. Marmer, an outstanding tide expert with the former U. S. Coast and Geodetic Survey, presents several examples of both the separate and combined influences of perigean spring tides in increasing the tidal range. He describes, in quantitative terms, the percentage increase in the daily range of the tides produced by the combination of the phenomena of perigean tide and syzygian (spring) tide, but does not actually define the resultant perigee-spring tides by name.

Reference sources and glossaries published in the 1940s to 1970's relating to oceanography and tides show a similar inexplicable lack of mention of the phenomenon of perigee springs, for example:

The *Manual of Harmonic Analysis and Prediction of Tides,* U. S. Coast and Geodetic Survey (National Ocean Survey) Special Publication No. 98, revised (1941) edition includes no mention of this type of tide.

The Admiralty Manual of Tides, by A. T. Doodson and H. D. Warburg, London (1941) likewise does not contain any reference to this term.

A similar omission occurs in *Waves, Tides, Currents and Beaches:* Glossary of Terms and List of Standard Symbols, by Robert L. Wiegel, published by the Council on Wave Research, The Engineering Foundation (1953).

The *Glossary of Oceanographic Terms,* Special Publication No. 35 of the U.S. Naval Oceanographic Office (1966) lists perigean tide and spring tide, but does not include the combined designation, perigee springs.

The Tide and Current Glossary, U. S. Coast and Geodetic Survey (National Ocean Survey) Special Publication No. 228, revised (1975) edition, included a definition of perigean tides and tidal currents, as well as spring tides, but did not list the combining form, perigean spring tides. (The term is to be included in a forthcoming new edition.)

Other glossaries and basic reference sources published prior to very recent years reveal the same basic oversight.

As a notable exception, in a book, *Coasts, Waves, and Weather* (1945), by an astronomer-meteorologist, John Q. Stewart, late of Princeton University, he gives specific graphical examples of the exceptional heights and depths attained by the high and low phases, respectively. of perigean spring tides. He also mentions the possible practical utilization of the flood stage of such tides in navigation over coastal bars.

Since that time, a noticeable gap seems to exist in any more recent literature which deals specifically with the topic of perigean spring tides. A computerized literature search through title, abstract, and other bibliographic data banks available in NOAA's OASIS (*O*ceanic and *A*tmospheric *S*cience *I*nformation *S*ystem), covering the general period from the 1960's to the present, reveals a singular absence of pertinent source literature, and not one article bearing the words "perigee springs," or "coastal flooding" in the title. The considerable bank of bibliographic sources (data bases) in the OASIS system searched for relevant citations, and their available periods of coverage, are: *Oceanic Abstracts* (1964–present), *Meteorological and Geoastrophysical Abstracts* (1972–present), *Geophysical Abstracts* (1966–70), *Selected Water Resources Abstracts* (1968–present), *Defense Documentation Center* (1953–present), *NASA Information Bank* (1962–present), and *Government Reports Announcements* (1964–present).

Following Stewart's work, the subject of perigean spring tides seems to have fallen almost into oblivion for 20 years. With the rapid advances of knowledge made possible during and after the International Geophysical Year (1959–60)—and through orbiting artificial satellites—there came a new interest in astronomically induced cyclical events, including the gravitational and tidal influences of the other bodies of the solar system upon various solar and terrestrial phenomena. Among the books of this new body of literature which are related to tides. three of the modern semitechnical references (of British and German origin) listed in the bibliography at the end of this volume contain a brief mention of perigean spring tides.

The great tidal flooding of March 6–7, 1962, although an outstanding example of a wind-induced coastal inundation associated with a perigean spring tide (chapter 7, Case 4), is designated in nearly all published sources only as a "spring tide."

Continuing and expanding on the vein of the previously cited article by Hans Pettersson, an article on "Earth Motions" by Clyde Stacey in *The Encyclopedia of Atmospheric Sciences and Astrogeology* (1967) describes the various special combinations of gravitational forces which produce maximum perigean spring tides.

None of the sources previously listed discusses the recurring short-range potential for tidal flooding associated with perigean spring tides in terms of: (1) the accelerated growth (and relaxation) rate of the tide curve around the time of perigee-syzygy: (2) the lengthening of the tidal day which extends the period of time during which tidal waters are subject to increased gravitational forces at the time of perigee-syzygy; (3) the corresponding increase in velocity of tidal currents, following an analogous pattern of increase in horizontal flow rate at time of perigee-syzygy; (4) the possibility of an enhanced coupling action of sea-surface winds with the inmoving tidal currents under these conditions of accelerated water flow; and (5) the establishment of a practical statistical measure (or coefficient) indicating the potential for, and probable severity of, tidal flooding subject to the foregoing astronomical circumstances, should strong, persistent, onshore coastal winds also prevail at the time. As will be taken up variously in the following chapters, it is these topics, together with supporting evidence and newly derived data relative to the hypotheses and theories advanced, which constitute the justification for the present research monograph.

In recapitulation, it is evident from the foregoing summary that the causal connection between perigean spring tides and the astronomical phenomenon of perigee-syzygy was a topic of early, although in no sense definitive scientific recognition. Moreover, a strange and inexplicable dearth of investigations has existed historically, in connection with the tidal flooding consequences resulting from a coincidence of this gravitational-force concentrating astronomical configuration and a reinforcing wind from the sea. This lapse has taken place also at a time marked by a great proliferation in real estate and recreational development along the North American coastline. An equally inexplicable hiatus has occurred in the application of ongoing research technology to the practical implications of this problem.

With consideration both to the number of years and the frequency of cases of coastal flooding represented among the newspaper accounts in chapter 1, it is obvious that the significance of this astronomically induced tidal phenomenon, when combined with adverse wind effects, has not received the attention it deserves. The increased potential for major coastal flooding associated with this particular type of tide has never been adequately brought out in the literature. Nor, in this same enhanced possibility for coastal erosion, inundation, and structural damage, have its impacts upon coastal geography and upon various marine-engineering, economic, and ecological phases of the coastal environment been duly emphasized.

Particularly is this true as the result of today's rapidly burgeoning real estate development, involving extensive housing and condominium expansion along the coastline. A case-study investigation is long overdue on the cause-and-effect relationships underlying examples of major tidal flooding (both associated with winter storms and induced by hurricanes) on the North American coastline during the more than 340 years over which historical records exist. Such a study is offered here.

Part II—Scientific Analysis

Chapter 1.

General Background Consideration of Astronomical Positions and Motions Important in the Evaluation of Perigean Spring Tides

The regular and obviously harmonic astronomical relationships which make possible the "equilibrium theory" of the tides are summarized in the appendix to this volume. Only those supplementary aspects pertaining to the creation, augmentation, and ultimate maximization of perigean spring tides will, therefore, be included as a descriptive adjunct in the technical portion of this text. In following this plan of presentation, the present introductory chapter will serve to clarify the text usage of specific astronomical terms used in the discussion of perigean spring tides, and also assist in the interpretation of the corresponding tidal terms of reference. In succeeding chapters, the discussion will narrow-in by increasingly more specialized stages to consider, in turn, various dynamic factors which produce the precise astronomical alignments, close lunar distances, and combinations of gravitational forces responsible for the increased amplitudes of perigean spring tides.

Astronomical Factors Significant to Tidal Nomenclature

The tides in the Earth's oceans are caused entirely by the gravitational attraction of the Sun and Moon acting upon these water masses and, in determining and predicting the rise and fall of tidal waters, only the changing interrelationships of these three celestial bodies need be considered. In discussing the distances, motions, and geometric relationships of the Moon and Sun as they affect the tides, the exact positions of these two bodies upon the celestial sphere are of primary significance. A brief summary of the alternative methods of defining these positions is, consequently, desirable.

Astronomical Positions

Although the positions of astronomical bodies are given in as many as five different reference systems, only three of these have any direct application to the tides. These are: the *horizon system,* involving azimuth and altitude; the *equatorial system* in which right ascension and declination are the basic coordinates; and the *ecliptic system,* utilizing coordinates of celestial longitude and latitude. A detailed explanation of these systems can be obtained in any astronomical textbook, and they will not be described further here beyond their immediate application to tidal problems.

COORDINATE SYSTEMS

1. Equatorial System

In the equatorial system, the basic reference circle is the Equator of the Earth projected upon the celestial sphere. An axis projected through the north and south geographic poles of the Earth and extended in either direction beyond to the two points of intersection with the celestial sphere locates the north and south celestial poles. Similarly, the Earth's Equator extended outward to intersection with the celestial sphere becomes the celestial equator. The celestial equator is at all points 90° removed from either of the celestial poles. The astronomical *declination* (δ) of a body is measured in degrees, minutes, and seconds of arc perpendicularly north or south from the celestial equator through 90° to the north or south celestial poles, in the same way that geographic latitude is measured on the Earth's surface.

In contrast to geographic longitude which is measured both east and west from Greenwich through 180° of arc, the corresponding astronomical coordinate of *right ascension* (α) in the equatorial system is measured only from west to east and usually in hours, minutes, and seconds of time through 24 hours, rather than in units of arc. It is measured around the corresponding 360° of the celestial sphere from a fixed position back to that same position again. The astronomical position chosen to become that of 0 or 24 hours is the point of intersection of the celestial equator with the ecliptic on the celestial sphere. The *ecliptic* is the apparent path of the Sun around the celestial sphere as the Earth pursues its annual motion of revolution around the Sun, causing the Sun to appear to revolve around the Earth in the same direction.

Since these two great circles, the celestial equator and the ecliptic, intersect at two points, known as the vernal equinox and autumnal equinox, the origin for the coordinate of right ascension is defined as that intersection corresponding to the vernal equinox, or ascending node of the Earth's orbit, where the Sun in its apparent annual motion crosses the celestial equator from south to north about March 21. This position is known both as the vernal equinox and First Point of Aries (♈). In the same fashion that geographic longitude is measured on Earth—but now proceeding continuously from west to east through 360°—right ascension is measured along the celestial equator at right angles to any hour circle on which a celestial object lies.

A second method of positional representation in the equatorial system is known as the *hour-angle subsystem.* This subsystem uses, in place of right ascension and declination, the coordinates of hour angle (h) and declination (δ). The coordinate of declination is defined exactly as before, and its usage is the same in both cases. However, the origin for the placement of zero hour angle is different. In the right ascension subsystem, the vernal equinox establishes the great circle corresponding to 0^h (the equinoctial colure). In the hour-angle subsystem, the 0° origin is located where (in the Northern Hemisphere) a great circle from the south point on the celestial sphere intersects the celestial equator before passing respectively through the zenith of the place, the north celestial pole, the north point on the celestial sphere, the nadir, and the south celestial pole.

This same great circle becomes the *celestial meridian* for the place of observation. The celestial meridian, which corresponds with a vertical circle of 0° azimuth, is also used in connection with the horizon system of coordinates later to be described, since it passes through the zenith, nadir, and principal cardinal points of the latter system as well as through the celestial poles of the present system. The celestial meridian consists of two branches. That portion of the meridian between the north and south celestial poles which contains the zenith is called the *upper branch,* and a celestial body which transits this portion is said to be in *upper transit.* The portion of the meridian containing the nadir is the *lower branch,* and the passage of a celestial body over this portion is termed *lower transit.*

Successive *hour angles* are measured from the celestial meridian along the celestial equator through 360°, in a direction opposite to that of right ascension (i.e., from east to west, or clockwise as viewed from the north celestial pole). Hour angles are also designated in units of degrees (°), minutes (′), and seconds (″) of arc rather than hours (^{h}), minutes (^{m}), and seconds (^{s}) of time as in the case of right ascension. Each location on the surface of the Earth has its own local meridian or origin for the measurement of hour angle. This subsystem is thus tied to the Earth itself and rotates with it, while the coordinate of right ascension (except for very small perturbational variations) remains essentially fixed with respect to the stars.

A series of great circles passing perpendicularly through the celestial equator, each separated by 15° or 1 hour in mean solar time from that next to it, and converging on the celestial poles, are known as *hour circles.* A different system of hour circles exists for every longitudinal position on Earth, and likewise rotates with the Earth. Angular differences between various local meridians and the Greenwich prime meridian in England, the origin for geographic longitude, are specified as the Greenwich hour angle (GHA) of the place. The GHA is given in degrees, minutes, and seconds of arc in the same manner that geographic longitude on the Earth's surface is commonly expressed.

An important distinction is thus evident between the right ascension and hour-angle subsystems: Subject to the rotation of the Earth (i.e., the diurnal motion) the positions of all celestial bodies will continuously vary through 360° in hour angle during one complete rotation of the Earth from 0° on the celestial meridian to 0° again. However, the right ascension of a celestial object will not vary as the result of the Earth's rotation, but only if the object possesses its own motion in right ascension, or a component thereof.

Thus, the hour-angle subsystem becomes especially useful in evaluating the various effects of the Earth's daily rotation upon the tides. Since the position of the vernal equinox apparently moves through the same angle but in an opposite direction to the Earth at each rotation thereof, just as the Moon and Sun do in their apparent diurnal motions, the right ascension system is not useful for expressing the relative motions of these two bodies, when the rotation of the Earth must be considered.

The hour-angle subsystem does permit measurement to be made with respect to the rotating Earth. As the Earth rotates on its axis once in each 24 hours, in a west-to-east direction, the celestial object will describe a corresponding circle on the celestial sphere, but in the opposite direction, from east to west. Depending upon whether the object is located at a position directly on the celestial equator (declination = 0°) or at some angular distance in declination either north or south of the celestial equator, the circle thus described will be a great circle or small circle, respectively.

This apparent motion of the celestial object along a circle either coincident with, or parallel to, the celestial equator as the Earth rotates will prove to be a sizable advantage in tidal analysis where, for example, as a function of the Earth's diurnal rotation, the necessary catch-up time between a point on the surface of the Earth and the orbiting Moon is required.

2. Ecliptic System

The ecliptic system uses for its fundamental plane the plane of the Earth's annual revolution around the Sun. As in the right ascension subsystem, the coordinate of *celestial longitude* (λ) is measured eastward through 360° from the vernal equinox, but in the plane of, or parallel to, the ecliptic rather than the celestial equator, and in degrees, minutes, and seconds of arc rather than time. (As viewed from the north pole of the ecliptic, celestial longitude is measured in a direct, or counterclockwise sense of rotation.)

The coordinate of *celestial latitude* (β) similarly is measured in degrees, minutes, and seconds of arc directly north or south of (i.e., along ecliptic meridians at right angles to) the plane of the ecliptic. It reaches 90° at the north or south poles of the ecliptic. Subject to perturbations, β for the Moon ranges only from about 4°56′ to 5°20′.

Because the orbit of the Moon does not lie exactly in the plane of the ecliptic, but is inclined at a very small angle averaging 5°9′ to it, an acceptable artifice will later be used (pt. II, ch. 4) in defining either the true or mean longitude of the position of lunar perigee. Here the longitude of the perigee of the Moon's orbit, referred to either the mean or the true equinox of date, is measured from the vernal equinox along the ecliptic to the mean (or true) ascending node, and then along the Moon's orbit. (The ascending node of the Moon's orbit is the point of intersection of the Moon's orbital plane with the ecliptic, at that position where the Moon crosses this plane from south to north.)

The advantage of the ecliptic system is that it eliminates the inclination of the Earth's axis of rotation with respect to the ecliptic, and it is particularly useful when the Sun's apparent annual motion and the motions of the Moon with reference to it are concerned.

3. Horizon System

The horizon system is localized in that it involves the position of a celestial body as seen from a given point of observation on the surface of the Earth. The celestial body's coordinates of azimuth and altitude as used in this system are, therefore, topocentric rather than geocentric as in the two previous instances.

The astronomical *horizon* is a plane perpendicular to the local direction of gravity; the *zenith* is the point where this local direction of gravity intersects the celestial sphere. The coordinate of *azimuth* (Z), is measured in the plane of the horizon, in degrees, minutes, and seconds of arc through 360° in a clockwise (westerly) direction as viewed from the local zenith of the place. In various usages in astronomy, geodesy, navigation, and oceanography, the point of reference for 0° azimuth may be either the north or south point on the horizon. In calculations employed in connection with tides, the azimuths of tide-producing bodies are usually measured from the south through the west. However, the azimuth or "set" of a tidal current is that direction toward which it is flowing, commonly reckoned from the north point on the horizon.

In this system, vertical angular distances are measured (in one direction only) above the astronomical horizon through 90° toward the astronomical zenith. The measurement is in degrees, minutes, and seconds of arc. This positional coordinate representing angular distance above the horizon is known as astronomical *altitude* (H). Small circles of equal altitude parallel to the horizon are termed *almucantars;* great circles perpendicular to the horizon and passing through the zenith are *vertical circles.*

The vertical circle passing through the north and south points on the horizon, plus the zenith, nadir, and north and south celestial poles, is called the *celestial meridian.*

The horizon system is especially valuable for measuring the times and circumstances of rising and setting of celestial objects with respect to the astronomical horizon, since this plane is the basic reference plane for the system. It is also valuable in determining positions in terms of the cardinal points of the compass, and for making comparisons with other local geographic or geodetic positions on the Earth's surface.

Since the Moon is relatively close to the Earth compared with other celestial bodies, and the figure of the Earth is that of an irregular spheroid (or *geoid*), the Moon's parallax and distance from the surface of the Earth vary considerably at any angular altitude above the horizon. This system therefore has a particular usefulness in connection with tides in establishing the local zenith distance of the Moon. The latter function enters into the computation of parallax as a measure of distance of the Moon from the surface of the Earth, as well as in the lunar augmentation (see figs. 41, 25A, pt. II, chs. 4, 2).

GENERAL EQUATIONS FOR TRANSFORMATION OF COORDINATES FROM THE EQUATORIAL TO THE ECLIPTIC SYSTEM OR THE REVERSE

Where α and δ are the apparent right ascension and declination, respectively, of a celestial body; λ and β represent its corresponding celestial longitude and latitude; and ϵ is the obliquity of the ecliptic, or angle of inclination between the celestial equator and the ecliptic:

$$\begin{aligned} \sin\beta &= \sin\delta\cos\epsilon - \cos\delta\sin\alpha\sin\delta \\ \cos\beta\sin\lambda &= \sin\delta\sin\epsilon + \cos\delta\sin\alpha\cos\delta \\ \cos\beta\cos\lambda &= \cos\delta\cos\alpha \end{aligned}$$

and

$$\begin{aligned} \sin\delta &= \sin\beta\cos\epsilon + \cos\beta\sin\lambda\sin\epsilon \\ \cos\delta\sin\alpha &= \cos\beta\sin\lambda\cos\epsilon - \sin\beta\sin\epsilon \\ \cos\delta\cos\alpha &= \cos\beta\cos\lambda \end{aligned}$$

GENERAL EQUATIONS FOR TRANSFORMATION OF COORDINATES FROM THE EQUATORIAL TO THE HORIZON SYSTEM OR THE REVERSE

Where z is the zenith distance, A is the azimuth, H is the altitude, and δ is the declination of a celestial body; and ϕ is the latitude of the place of observation:

$$\begin{aligned} \sin z\sin A &= -\cos\delta\sin H \\ \cos z &= \sin\delta\sin\phi + \cos\delta\cos H\cos\phi \\ \sin z\cos A &= \sin\delta\cos\phi - \cos\delta\cos H\sin\phi \end{aligned}$$

and

$$\begin{aligned} \cos\delta\sin H &= -\sin z\sin A \\ \sin\delta &= \cos z\sin\phi + \sin z\cos A\cos\phi \\ \cos\delta\cos H &= \cos z\cos\phi - \sin z\cos A\sin\phi \end{aligned}$$

Astronomical Motions

The Earth is constantly undergoing no less than seven astronomical motions, each of which causes a displacement (ranging from an almost inconsequential to a major amount) in the positions of bodies in space. These motions are: (1) the diurnal rotation of the Earth; (2) the annual revolution of the Earth around the Sun; (3) the precession of the equinoxes; (4) the nutational motion of the polar axis; (5) the space motion of the Earth with the Sun toward the apex of the Sun's way; (6) the rotation of the galaxy around its center; and (7) the irregular shifting of the Earth's crust, as the geographic pole of the Earth is displaced at a nonuniform rate, and for a yet uncertain complex of dynamic reasons, with respect to its pole of figure—a motion responsible for the phenomenon of "variation of latitude."

In terms of the tides, only two of the above motions are of consequence. These are the diurnal rotation of the Earth and the annual revolution of the Earth around the Sun. In addition, it is necessary to consider the monthly revolution of the Moon around the Earth. The effect of the Moon's position in declination upon its rate of change in right ascension must also receive attention.

THE DIURNAL ROTATION OF THE EARTH

Although all four of the motions mentioned in the immediately preceding paragraph are physical and real, the effective measurement of each is made in terms of an apparent change in position, or the displacement of the Moon and Sun on the celestial sphere produced thereby. The diurnal rotation of the Earth will be considered first.

The actual daily rotation of the Earth results in a phenomenon similar to that observed as a moving car or vehicle catches up on another object and passes it. In what is a purely fictitious or unreal motion, the object thus passed, although stationary or moving at a slower rate in the same direction as the passing body, drops behind it and seems to move in a direction opposite to that of the latter.

In the same fashion, the Earth rotates daily on its axis against the background of stars which, because of their enormous distances, may be assumed to be "fixed." As a result, these objects drop back and appear to move in a direction opposite to that of the rotating Earth, and at exactly the same angular speed. Since any point of observation on the Earth's surface is moving in a circle around the Earth's axis of rotation, each object on the celestial sphere likewise appears to move in a circle. Both the radius of the circle projected perpendicularly to this axis of rotation and the object's consequent apparent speed of rotation become successively less as the object's position is located farther from the celestial equator. Subject to the diurnal rotation of the Earth, all celestial objects (except meteors) appear to rise in the east, move across the sky, and set on the western horizon. The independent motions of the Moon, Sun, and planets among the stars will be discussed separately.

At the vast distances of the stars, any individual motions which the stars possess are detectable only through precise measurements, and even over centuries of time the configurations and relative positions of these objects as seen from the Earth are subject only to the minute cross-motion components of proper motion. As the stars appear to rise and set, subject to the Earth's diurnal rotation, they may be thought of as attached to the surface of a vast sphere, which itself rotates daily around the Earth from east to west as a reflection of the Earth's rotation from west to east.

Thus, any given star crosses the hour angle of the vernal equinox (the origin of right ascension) at approximately the same time in each 24-hour period (actually, because of the Earth's annual revolution, about 4 minutes earlier at each transit thereof). The coordinate positions of the stars—except for certain long-period changes—thus remain essentially unaltered. This makes it possible to compile star catalogs in which the right ascensions and declinations vary only in small units or decimal portions of seconds of time and arc (due to the common-motion phenomena of precession, nutation, and aberration, as well as proper motion, etc.) over long periods of time.

The Moon and Sun likewise rise and set in accordance with the diurnal rotation of the Earth but have, in addition, both real and apparent motions of their own which considerably modify their diurnal motions as induced by the rotating Earth. The Sun's apparent motion will be discussed first.

THE EARTH'S ANNUAL REVOLUTION AROUND THE SUN

The annual revolution of the Earth is responsible for a second instance of an apparent, fictitious motion—that of the Sun. As the Earth revolves around the Sun in a direction which is counterclockwise as viewed from the north pole of the ecliptic (i.e., in the same direction as the Earth's rotation), the object around which it revolves will itself seem to revolve around the Earth, in this case moving in the same direction as that of the Earth's revolution. The Moon is, of course, bound to the Earth by gravitational attraction, and partakes of the Earth's revolution around the Sun, while at the same time it individually revolves around the Earth. The Moon, therefore, does not appear to revolve counterclockwise, or eastward in the sky, *from this particular cause* as does the Sun. The apparent annual solar motion is equivalent to 360°/365.25 days, or approximately 1°/day, on the average, in celestial longitude (fig. 22).

The period of time between two successive alignments in longitude of the Sun, Earth, and a given star (the sidereal year) is 365.25636042 days; between similar successive alignments with the vernal equinox (the tropical year), 365.24219879 days; between successive solar perigees (the anomalistic year), 365.25964134 days; and between successive passages of the Earth through the ascending node of its orbit (the eclipse year), 346.620031 days.

As the Earth moves physically in a counterclockwise or "direct" sense of motion around the Sun, the Sun *appears* (in a purely fictitious manner) to move in the same direct sense of revolution as seen from the north pole of the ecliptic. This apparent easterly motion must be subtracted from the apparent daily westerly motion of rising and setting caused by the Earth's rotation. The Sun (if its image could be observed for 24 hours a day, 365¼ days in the year) from a nonrotating Earth would move easterly across the sky, completing one full revolution in 365¼ days. Its average easterly movement is 360° (equivalent to 24 hours or 1,440 minutes of time) divided by 365¼ days, or slightly less than 4^m/day.

From this cause alone, the Sun's right ascension should increase by close to this same amount during each day. Actually, however, as a result of other circumstances, namely, the elliptical shape of the Earth's orbit and the inclination of the celestial equator to the ecliptic (causing a continuously changing declination of the Sun), the observed change in right ascension follows a pattern related directly to these factors. The daily increase in the Sun's right ascension is least at the equinoxes and greatest at the solstices, the maximum annual increase being at the winter solstice since this is also close to perihelion. (See ch. 2, table 9.)

To establish a uniform basis for timekeeping, the concept of a purely fictitious or *mean sun* is resorted to, in which this hypothetical celestial body is assumed to move at all times along the celestial equator rather than the ecliptic, and at constant angular velocity. Thus, whereas the average value of the true sidereal day is $23^h\ 56^m\ 04.09054^s$ of mean solar time, the mean solar day has a length of exactly $24^h\ 00^m\ 00^s$ mean solar time, which is equivalent to $24^h\ 03^m\ 56.55536^s$ of mean sidereal time.

THE MOON'S REVOLUTION AROUND THE EARTH

Finally, the Moon revolves around the Earth (fig. 22) in the same direction and sense of revolution (i.e., counterclockwise viewed from the north pole of the ecliptic) in

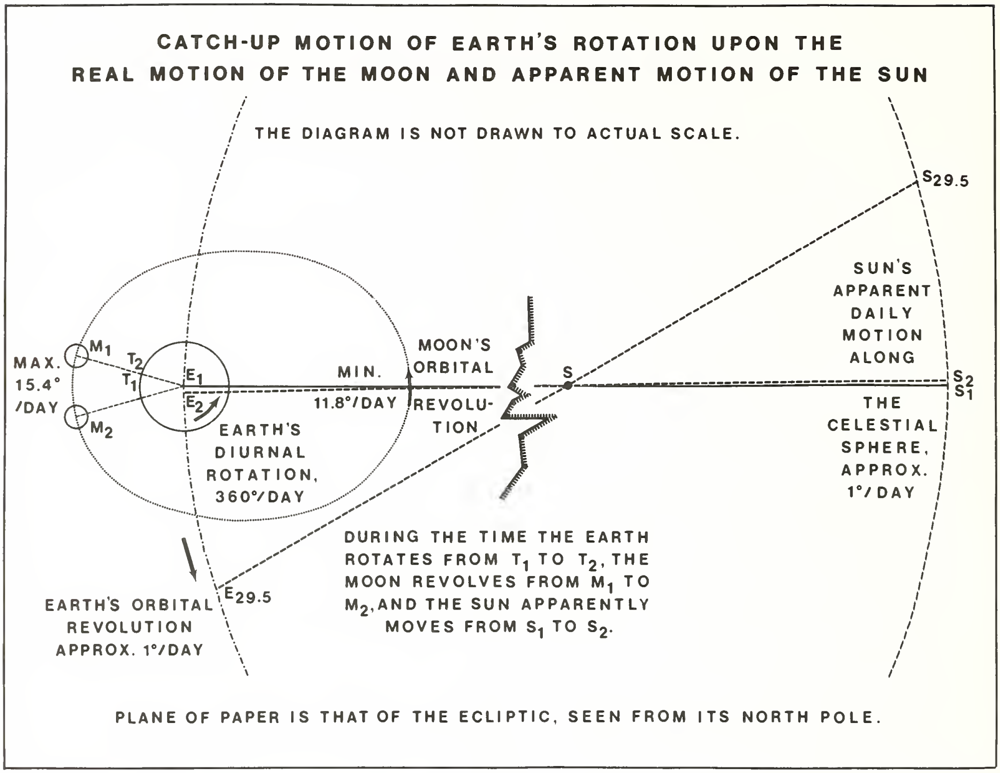


FIGURE 22

which the Earth revolves around the Sun. This results in an apparent motion of the Moon in the same direction as that of the Sun, but of greater magnitude because the Moon is both closer to the Earth and moving faster. It must also be remembered that the basic revolutionary motion of the Moon is a real one rather than an apparent one conjugate to the annual motion of the Earth as in the case of the Sun.

The true revolution of the Moon around the Earth in a period of one *sidereal month,* from alignment with a given star to alignment with that same star again, requires 27.321661 days.

The *tropical month* (the period between two successive alignments of the Moon's position with the longitude of the vernal equinox) is 27.321582 days. Because of the slow westward (retrograde) movement of the vernal equinox caused by the precession of the equinoxes, this month is shortened by 0.000079 day with respect to the sidereal month.

The *draconitic or nodical month* (measured by two successive transits of the Moon through the longitude of the Moon's ascending node—or position of intersection between the northward-inclined lunar orbit and the ecliptic) is equal to 27.212220 days. It is likewise shortened with respect to the sidereal month by the regression of the lunar nodes subject to gravitational perturbations induced by the Sun.

The *synodic month* is the period of time between alignment of the Moon and Sun in identical longitudes (or right ascensions) and the next succeeding occurrence of this same syzygy position. It is thus equivalent to the interval between two successive conjunctions (new moons) or oppositions (full moons) and is equal to 29.530589 days.

This considerable lengthening of the synodic month over the period of the sidereal month is explained by the fact that, at the same time the Moon revolves around the Earth, the Earth revolves around the Sun, carrying the Moon with it, bound together by their mutual gravitational tie.

As the Earth physically revolves around the Sun in its annual motion, the Sun *appears* to revolve around the Earth in the same period, at the same angular velocity, and in the same easterly direction. Accordingly, the apparent annual motion of revolution of the Sun occurs in the same direction as the actual monthly revolution of the Moon around the Earth. Although the velocity of the Moon in its orbit is much faster than the apparent motion of the Sun along the ecliptic, the Moon must each month travel somewhat farther in its orbit to catch up with the motion of the Sun and achieve alignment with it at position of syzygy.

The extra period of time required in this catch-up motion is 2.208928 days longer than the sidereal period, which accounts for the longer synodic month of 29.530589 days.

If one were to consider only the motion of the Moon with respect to the stars and the length of the sidereal month as previously defined, the Moon would appear to drop back in its daily westward motion of rising and setting (i.e., drift slowly eastward in the sky) by approximately 360°/27.321661 days, or 13.176396°/day—later defined as the lunar *mean daily motion*. However, as will be seen, factors exist to alter this average angular velocity of the Moon, both with respect to the Sun and relative to any point on the surface of the rotating Earth.

Because of the Earth's motion in orbit around the Sun, and the Sun's consequent apparent easterly motion in the same direction as the Moon, the Moon appears to move at the somewhat reduced average angular velocity with respect to the Sun given by 360°/29.530589 days, or 12.190749°/day. It is this apparent motion of the Moon in catching up and passing, and thus moving respectively toward and away from the Sun in angular elongation, that produces the continuously changing lunar phase relationships.

It is important to note that the apparent motions of both the Moon and the Sun in the sky (the former caused by the Moon's orbital motion, the latter by the Earth's annual revolution) are in a direction *opposite to the motion of rising and setting* which results from the rotation of the Earth. The apparent daily motions of the Sun and Moon caused by these respective two factors are, however, *in the same direction as that of the rotating Earth*. This fact is very significant in connection with a further daily catch-up motion of the rotating Earth with the positions of the Moon and Sun. The corresponding influence of the apparent eastward drift of the Moon in the sky, causing it to transit the celestial meridian some 50 minutes later each day, will be discussed in an ensuing section on the lunar retardation.

THE MOTIONS OF THE EARTH AND MOON IN ELLIPTICAL ORBITS

It previously has been indicated that the orbit of the Earth around the Sun is not circular, but elliptical in shape, with the Sun occupying one of the two foci of the ellipse. (See fig. 4 in the appendix.) It may be noted by direct analogy that the Moon also revolves around the Earth in an elliptical orbit, with the Earth at the occupied focus of the ellipse (fig. 23). The dynamic principles of orbital motion are exactly the same in each instance, and a single discussion of the general forces involved will suffice for both.

By definition, an ellipse is a geometric section constructed by passing a plane obliquely through a cone. The linear circumference of the resulting figure has an "out-of-round" configuration whose greatest diameter is described as the *major axis* and the least diameter (bisecting, and at right angles to, the first) is designated as the *minor axis*. By definition, the *mean distance* of any celestial object moving in an ellipse is equivalent to the semimajor axis. The extent of out-of-roundness is described as the *eccentricity,* whose value varies from 0 for a true circle, through very high values for a thin, very greatly extended ellipse, to infinity for a straight line. The eccentricity is defined by the ratio OC/OA in figure 23. The so-called *angle of eccentricity* is represented by the angle OBC in this same figure, and the sine of this angle is often used in astronomical computations.

Kepler's First Law of Planetary Motion states that all planets (and satellites) in the solar system move in elliptical orbits, with the less massive or secondary object revolving around its more massive or primary object.

Kepler's Second Law states that the distance of the secondary object from its primary is always such that the radius vector or line drawn from the primary object to its secondary will describe equal areas in equal intervals of time. It is clear from figure 24 that, no matter where in the ellipse a body is located, an area is defined between two radius vectors drawn to different positions of the object in orbit and the arc of the orbit along which this secondary object travels. The area circumscribed by these two lines and the arc joining the two positions of the object will always be the same. For example, in figure 24, $A_1 = A_2$.

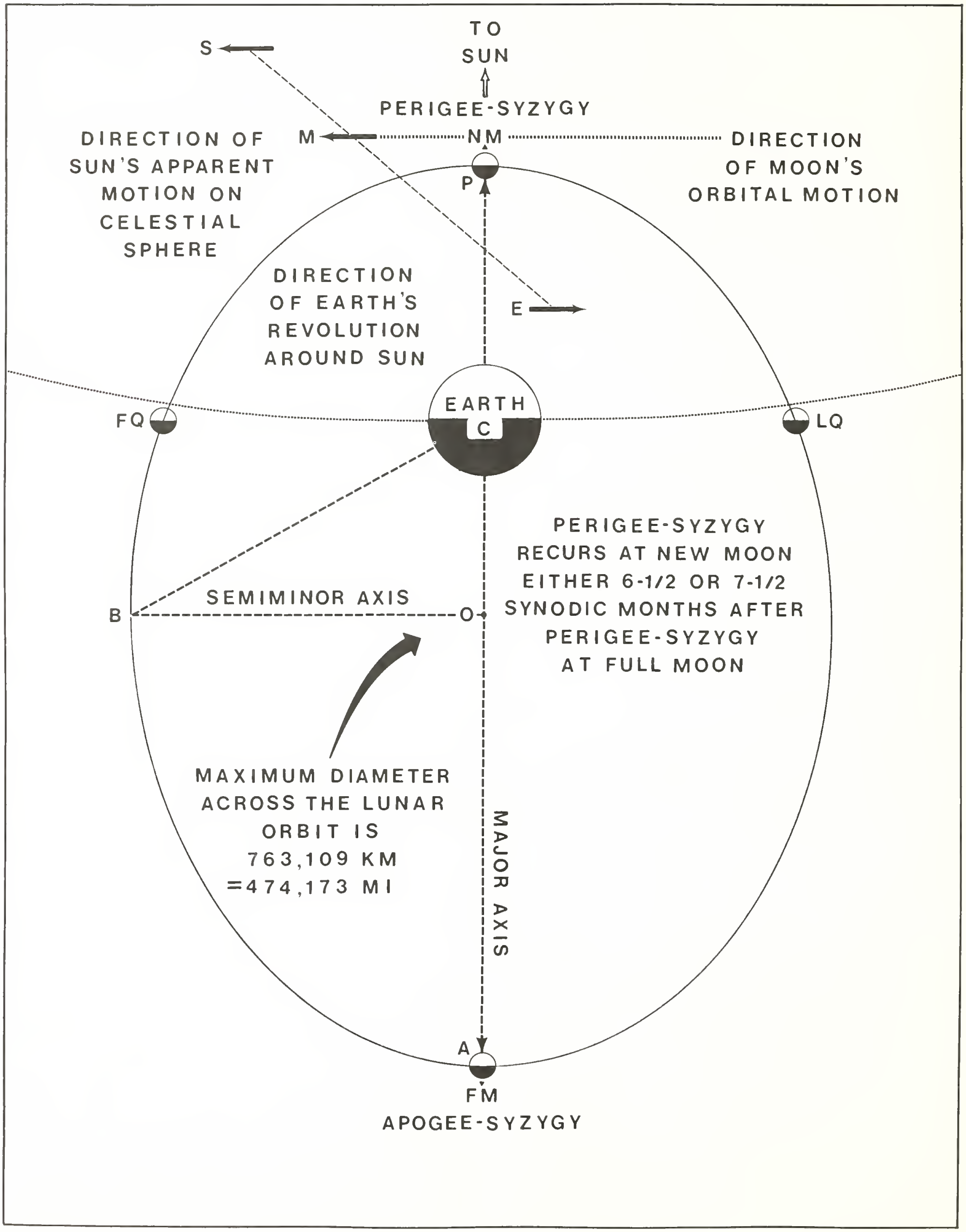
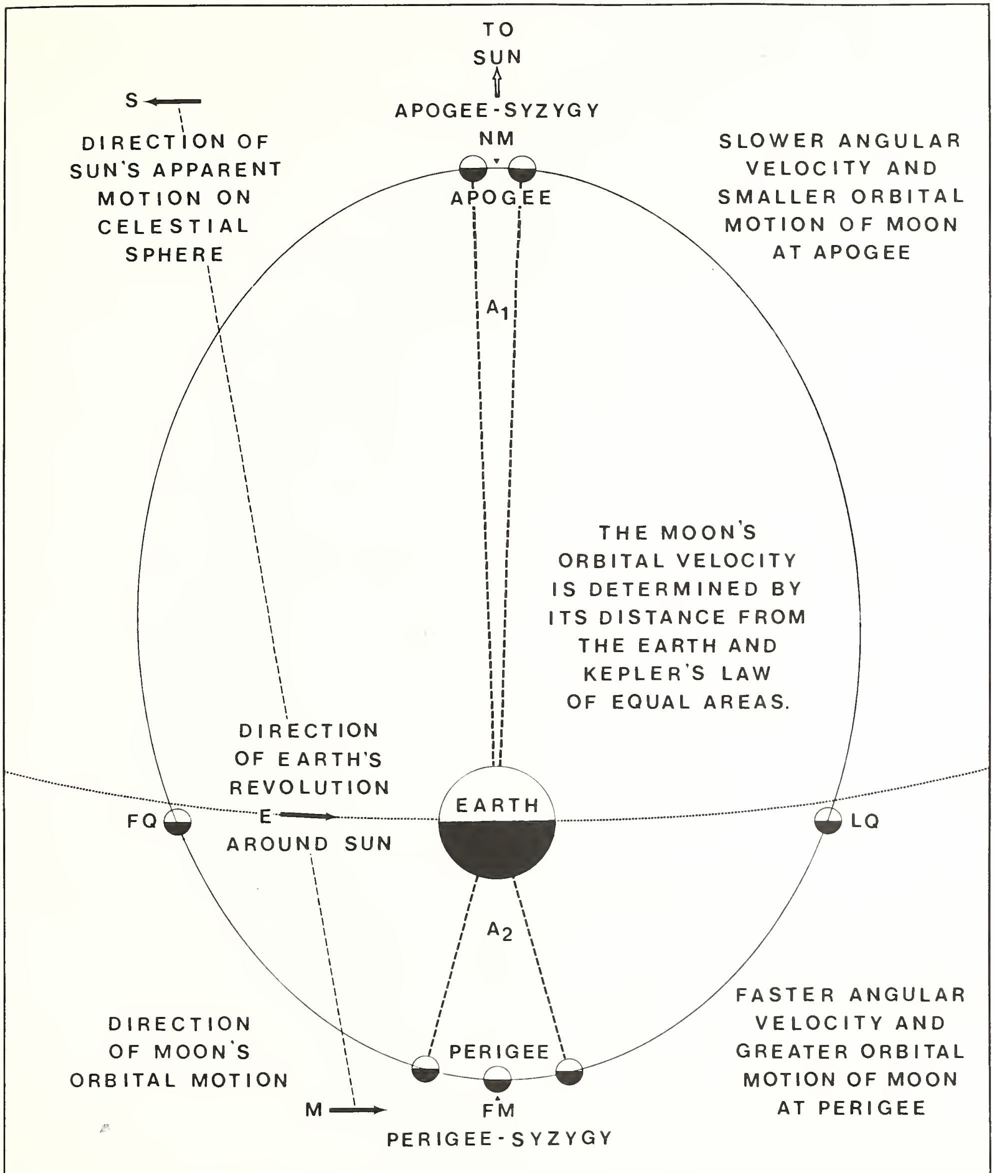

S
TO
SUN
PERIGEE-SYZYGY
DIRECTION OF SUN'S APPARENT MOTION ON CELESTIAL SPHERE
M
NM
DIRECTION OF MOON'S ORBITAL MOTION
P
DIRECTION OF EARTH'S REVOLUTION AROUND SUN
E
EARTH
FQ
C
LQ
PERIGEE-SYZYGY RECURS AT NEW MOON EITHER 6-1/2 OR 7-1/2 SYNODIC MONTHS AFTER PERIGEE-SYZYGY AT FULL MOON
SEMIMINOR AXIS
B
O
MAXIMUM DIAMETER ACROSS THE LUNAR ORBIT IS 763,109 KM =474,173 MI
MAJOR AXIS
A
FM
APOGEE-SYZYGY

Figure 23



<u>NOTE</u>: FOR CLARITY OF PRESENTATION, BOTH THE ORBITAL ECCENTRICITY AND DAILY MOTION OF THE MOON ARE EXAGGERATED IN SOME DIAGRAMS OF THIS WORK.

FIGURE 24

202-509 O - 78 - 11

Kepler's Third Law states that the period of revolution of the secondary object revolving around its primary (or of two secondary bodies revolving around their individual primaries) will vary according to the relationship:

$$P_1^2/P_2^2 = d_1^3/d_2^3 \quad \text{(corrective terms for the masses are omitted)}$$

In words, the square of the period of revolution varies from one time to another (or one object to another) as the cube of the mean distance between the object and its primary during the interval concerned.

The direct implication of these three astronomical laws is that, as the Moon revolves around the Earth in its monthly orbit, at one position in its orbit known as *perigee* it will reach its closest monthly approach to the Earth and, approximately one-half month later, will reach its greatest monthly distance from the Earth known as *apogee.*

Similarly, in the Earth's annual motion around the Sun, about January 2–4 it will pass through a position of closest approach to the Sun known as *perihelion* and, around July 3–6, 6 months later, will pass through a position of greatest distance from the Sun known as *aphelion.*

Since, in each case of closest approach (perigee or perihelion) of the less massive object to its primary, the gravitational force of attraction exerted between the primary and secondary is greater, the secondary object will also "fall" faster toward its primary at this point. With this increased inwardly directed gravitational or centripetal force being balanced by a correspondingly enhanced outwardly directed centrifugal force, the secondary object remains constrained to move in a closed elliptical orbit. Because of the increased gravitational force involved at this closer distance of approach, the speed of the secondary object in its orbit also will be greater, and the resulting angular distance the object will travel in any unit of time will be larger (fig. 24).

Just the opposite is true at apogee or aphelion, with the secondary object revolving at a considerably slower speed in orbit and covering a much smaller distance (this applies in either a linear or angular sense).

The maximum and minimum daily angular velocities of the Moon are about 15.4° and 11.8°, respectively; those of the Sun are approximately 1.016° and 0.983°. The length of the anomalistic month (from perigee to perigee) is 27.554551 days, and that of the anomalistic year (from perihelion to perihelion) is 365.25964134 days. The differences between both these values and the corresponding sidereal periods are the result of perturbations which cause a net forward motion of perigee and a retrograde motion of perihelion, respectively.

With these new concepts in mind, it is necessary to return to the previously mentioned elliptical motions of the Moon around the Earth and the Earth around the Sun. The next step is to discover how such continuously changing, rather than constant, apparent angular motions of both the Moon and Sun, together with their positions of closest approach to the Earth, affect various astronomical configurations and alignments, and the mean or average time intervals between successive such alignments. The procedures by which these different intervals are quantitatively evaluated also will be indicated.

1. The Anomalistic Month

The period of time between two successive passages of the Moon through the position of perigee is known as an *anomalistic month.*

Determination of the mean length of this month is analytically complicated by the fact that the perigee position of the Moon's orbit oscillates periodically, but by unequal amounts, in a direct and retrograde sense, due to perturbations produced by the Sun. A simplified representation of the length of the mean anomalistic month may, however, be achieved from the arbitrary assumptions that: (1) the perigee position is moving constantly and uniformly around the lunar orbit in the same direction as the Moon; and (2) this average daily forward motion of the lunar perigee along the Moon's orbit is +0.111404°/day.

Since the perigee completes one revolution around the lunar orbit in a period of 3,231.48 days (as calculated from observations secured over many years), this corresponds with the average rate of 360°/3,231.48 days, or 0.111404°/day specified above. The Moon revolves in its orbit at a mean sidereal rate (see below) of 13.176396°/day, a much faster angular velocity. In a recurring catch-up motion, which is not a part of the Earth's diurnal rotation, the Moon as seen from the Earth therefore moves once each month from a position to the west of (following) the lunar perigee, successively overtakes, draws in line with, and passes this position, and then advances to the east thereof.

The mean daily motion of the Moon in its orbital revolution around the Earth, as measured with respect to the "fixed" stars is given by:

$$\frac{360^\circ}{\text{sidereal month}} = \frac{360^\circ}{27.321661 \text{ days}} = 13.176396^\circ/\text{day}$$

This means that, with respect to the previously assumed, steadily advancing position of perigee, the Moon moves at a *relative* angular speed of:

$$13.176396°/\text{day} - 0.111404°/\text{day} = 13.064992°/\text{day}$$

By means of the latter value, the mean anomalistic period of revolution (from perigee to perigee) may be calculated as:

$$\frac{360°}{13.064992°/\text{day}} = 27.554551 \text{ days}$$

However, as previously indicated, this average figure is derived from the dual assumptions of: (1) a perigee position which moves continuously in a forward direction, and at a uniform speed, along the lunar orbit; and (2) a hypothetical or mean moon, which is moving constantly at the same speed in its orbit.

At the times of a close perigee-syzygy alignment, very different conditions actually hold true. At such times (later to be described as proxigee-syzygy), the perturbed motion of perigee is considerably different in both magnitude and direction from the mean value of $+0.111404°/$day given above. (See "The Special Motion of Perigee Close to the Position of Perigee-Syzygy Alignment" in pt. II, ch. 4.) At such times also, the orbital angular velocity of the Moon may attain an actual value as high as $15.4°/$day.

2. Effect of the Solar Parallactic Inequality

The quantity known in tidal theory as the *solar parallactic inequality* is that associated with the elliptical shape of the Earth's orbit. It arises from the fact that, revolving in this elliptical orbit, once in each half-year the Earth reaches its respective positions of closest annual approach to, and greatest distance from, the Sun, previously defined as perihelion and aphelion. As also noted earlier, the Earth is traveling at a considerably greater orbital velocity at perihelion, and a correspondingly diminished velocity at aphelion.

The fact that the actual orbital motion of the Earth results in a precisely similar, apparent motion of the Sun in the sky makes it possible empirically to evaluate the changing magnitude of this apparent solar motion by means of data tabulated in *The American Ephemeris and Nautical Almanac.* These data give the daily apparent positions of the Sun throughout the year. If the reflection of the Earth's own orbital motion were the only factor involved in the apparent velocity of the Sun's movement, the angular distance covered by the Sun in its apparent daily motion would be greatest near the time of perihelion and least near aphelion. It will be seen (table 7) that, in terms of right ascension, this is not entirely true.

Since the apparent daily motion of the Sun along the ecliptic is sufficiently representative to illustrate such effects of the Earth's position in orbit, the changing angular accelerations can be obtained simply by taking successive daily differences in the longitudes of the Sun. Subsequently, in applying the meaning of these different velocities of motion to tidal phenomena, allowance also will be made for the daily catch-up motion of the rotating Earth with the Sun. It will then be necessary in place of these motions in apparent or true (as distinct from mean) longitude to consider the corresponding motions in right ascension (thereby referring them to the equatorial plane of the Earth's rotation).

The apparent daily motion of the Sun does not vary widely from year to year and, to the order of accuracy required for the present purpose, may be obtained from *The American Ephemeris and Nautical Almanac* for any year. Thus, the average daily motions of the Sun in degrees of arc in celestial longitude and in seconds of time in right ascension, bracketing the perihelion of 1975 January 2 and the aphelion of July 6, as well as at the two solstices and two equinoxes, are given in table 7.

TABLE 7.—*Apparent Daily Motion of the True Sun in Right Ascension and Longitude for Selected Dates in 1975*

Circumstance	Nearest inclusive tabular dates	Apparent daily motion		True distance of sun, averaged for ecliptic of inclusive tabular dates (mean distance, $\oplus=1$)
		In α (^{s})	In λ ($°$)	
Perihelion: Jan. 2.	Jan. 3–2....	264. 60	1. 0190	0. 9832890
Aphelion: July 6.	July 6–5....	247. 16	0. 9536	1. 0167433
		17. 44	0. 0654	
Winter solstice: Dec. 22.5.	Dec. 23–22.	266. 36	1. 0182	0. 9836583
Summer solstice: June 22.	June 23–22.	249. 49	0. 9537	1. 0163006
		16. 87	0. 0645	
Vernal equinox: Mar. 21.	Mar. 22–21.	218. 67	0. 9931	0. 9961315
Autumnal equinox: Sept. 23.5.	Sept. 24–23.	215. 45	0. 9785	1. 0033977
		3. 22	0. 0146	

It is apparent from the preceding table that the greatest *difference* in the apparent daily motions of the Sun occurs when comparing the respective angular velocities at perihelion and aphelion. This is due to the greater orbital speed of the Earth and increased apparent motion of the Sun when the Earth reaches its closest annual approach to this massive body, and the corresponding decrease in apparent velocity of the Sun at aphelion.

However, as seen also from the second pair of examples, the difference in the Sun's apparent daily motions between the summer and winter solstices runs a very close second—since these dates occur within less than 2 weeks of aphelion and perihelion, respectively. Moreover, and even more important in terms of the subsequent description of solstitial tidal peaks (pt. II, ch. 2), the *individual values* of the daily apparent angular motions of the Sun at the times of the summer and winter solstices are higher than those at aphelion and perihelion, respectively. This indicates the effect of minimum daily motion in declination and a maximum motion in right ascension, as will be discussed in detail in various subsequent sections—with an introductory explanation under the immediately following heading.

Finally, the daily motion of the Sun at the times of either of the equinoxes is seen to be the least of all—evidence of a minimum motion in right ascension and maximum motion in declination. In the third set of data representing the apparent motions of the Sun at the times of the vernal and autumnal equinoxes, the small difference between the respective daily solar motions on these dates results from several possible causes: (1) an asymmetry in the Earth's orbit produced by a slow regression of the ascending and descending nodes along the ecliptic—such that the equinoxes are not necessarily symmetrically arranged with respect to the line of apsides joining perihelion and aphelion; (2) the recognized slow progression of the Earth's line of apsides along the ecliptic will have a similar effect; and (3) the date of the vernal equinox, around March 21, is closer to the perihelion date, about January 4 (and its effect in increasing the orbital velocity of the Earth), than the autumnal equinox, approximately September 23, is to this same perihelion date.

In consequence, within a day or two of the summer and winter solstices, as the positive and negative solar declination angles reach their respective maximum annual values, the daily differences in right ascension of the Sun also attain their greatest values and the daily differences in declination their least values for the year, as confirmed in table 7. Similarly, at those times, twice each lunar month, when the Moon reaches its maximum declination, either north or south of the celestial equator, the daily difference in the lunar declination becomes zero. Within a few days of this same date, the daily change in the right ascension of the Moon approaches a maximum value for that lunation.

Conversely, as the Moon and Sun in their apparent motions cross the Earth's Equator, their declinations become zero and change sign. At such times, especially for the Moon (due to its large parallax) and, to a lesser extent, for the Sun, the paths of their movements in declination have their greatest inclinations to the Equator and the differences in declination change the most rapidly. This situation is especially marked in terms of topocentric motions as the Moon reaches its extreme declinational values in the 18.6-year nodical cycle (see pt. II, ch. 4, "Effects of Extreme Lunar Declination . . .").

DECLINATIONAL EFFECTS ON THE APPARENT MOTIONS OF THE MOON AND SUN

In dealing with the changing tidal forces resulting from the varying positions and motions of the Moon and Sun, one factor is noteworthy as accelerating the apparent motions of these two bodies in right ascension. This, in turn, increases the Earth's necessary rotational catch-up time, lengthens the tidal day, and provides a greater opportunity for enhanced tide-raising forces to operate. The effect in question is that of a maximum lunar (or solar) declination angle in contributing to an increased motion of these respective bodies parallel to the celestial equator. Each of the apparent motions represented, when declination is plotted against increasing right ascension (or the passage of time) as in the top of figure 44, reveals a series of curve maxima and minima in declination.

Any such near-maximum value in declination means that the Moon or Sun, in attaining its greatest angular distance north or south of the celestial equator, is at a point where the slope of the curve is very nearly zero. Practically all of the movement of the body is in right ascension and very little, if any, is in declination. As the slope becomes zero at the peak of the curve, the daily differences in declination contrastingly become the smallest and, as they pass through zero, change their sign.

Auxiliary Influences Affecting the Daily Rate of Lunar Motion in Right Ascension

In the interests of completeness, it must be noted that several counterproductive astronomical forces exist, capable of altering the extra tide-raising potential created by situations in which the relative motions between Earth, Moon, and Sun are slowed down. As will subsequently be demonstrated, it is subject to this latter condition that augmented gravitational forces produced by the mutual alignment of these three bodies are exerted over a greater period of time in a lengthened tidal day, and enhanced tides result.

The Effect of Parallax on the Moon's Apparent Motion

In addition to the effects upon lunar motion associated with the two solstitial and two equinoctial positions previously described, another astronomical factor contributes to the respective circumstances that: (1) the Moon's apparent motion in right ascension often attains its largest value and the declinational motion reaches a minimum when the Moon is at or near its greatest declination (either north or south of the celestial equator); and (2) the Moon's greatest motion in declination and least motion in right ascension occurs when it is on or near the celestial equator. (All such comparisons of extreme motions refer specifically to the lunation in which the Moon is at the moment.)

This second contributing factor involves the considerable difference in the Moon's motion as calculated in (1) geocentric and (2) topocentric coordinates (i.e., as this motion would be observed respectively from the center of the Earth and from a point on its surface). The difference in apparent motion is caused by the relatively close distance to the Earth and large parallax angle (see figs. 41, 25A) of the Moon. Two other factors which must be considered as an integral part of the present discussion are (1) the apparent diurnal motion of the Moon, as a reflection of the rotation of the Earth, and (2) the individual or actual motion of the Moon in its own orbit, creating a positional displacement which is only vectorially related to the motion of the rotating Earth.

Changes in Right Ascension Associated With the Apparent Diurnal Motion of the Moon

The first of these two motions will now be discussed, employing the equatorial system of coordinates for reference, in order to illustrate the particular influence of lunar declination upon one of several possible variable motions of the Moon in right ascension—that is, the diurnal motion as seen from a topocentric position. (The diurnal motion of the Moon as used for purpose of comparison in the present connection has been defined as that occurring in a diurnal circle and resulting purely from the rotation of the Earth. In this usage, it does not contain the daily component of the Moon's own orbital motion. The term topocentric—referring to measurements made from the surface of a planetary body—also has been differentiated from the expression geocentric, referring to the Earth's center.)

The apparent diurnal motion of the Moon as seen from any given location on the surface of the Earth is, in topocentric terms, and as expressed in the equatorial system of coordinates, a function of two quantities which serve to relate the lunar position to this particular point of observation. These quantities are the geocentric latitude (ϕ) of the place and the hour angle (h) of the Moon. The latter value represents the angular distance of a celestial object east or west of the local meridian, measured at right angles thereto and, in this usage, expressed in equivalent units of time. Its value is positive when the object is west, and negative when it is east of the meridian. An additional parameter which is necessary to transfer the lunar position from a geocentric to a topocentric reference system is the distance of the Moon from the center of the Earth (given by π, the geocentric horizontal parallax at the time of observation).

The first two of the above quantities are different for each location on the Earth's surface, and the third changes continuously with time. The two remaining astronomical variables involved are denoted by $\Delta\alpha$ (the hourly rate of change of the Moon's position in right ascension) and δ (the instantaneous value of the Moon's declination).

The geometric relationships between these various quantities are expressed approximately by the formula given below. This represents the geocentric motion imposed on the Moon by the Earth's diurnal rotation, plus topocentric corrections to this motion introduced by: (1) the hour angle and parallax of the Moon; (2) its altered declination as seen from the Earth's surface rather than its center; and (3) the latitude of the observer.

$$\Delta\alpha\ (\text{topocentric}) = \Delta\alpha\ (\text{geocentric}) + \frac{\pi''\cos\phi\cos h}{57.3°/\text{radian}\ \cos\delta}$$

The analytic evaluation of $\Delta\alpha$ (geocentric) is given by

$$\Delta\alpha\ (\text{geocentric}) = \left[\frac{dh}{dt}\right]_G - \left[\frac{dh}{dt}\right]_T$$

At this point, a substantial technical digression is desirable, as a supplement to the main text, to explain the alternative method of positional representation in the equatorial system of coordinates, and at the same time quantitatively to evaluate the unknown analytic terms in the above equation.

In the equatorial system of coordinates, the Earth's axis is the primary reference, and its extension to the points of intersection with the celestial sphere demarcates the north and south celestial poles. The celestial equator lies in a plane perpendicular to this rotational axis and midway between the poles. It is around this axis that the diurnal motion constituting the immediate topic of discussion occurs. The apparent "rising and setting" motion caused by the rotating Earth changes the Moon's position with respect to the local meridian and hence its hour angle (see next paragraph), but does not alter its right ascension, since the established origin of this coordinate is, as far as the diurnal motion is concerned, also moving at the same angular rate. If the effect of the Earth's rotational motion were alone to be considered and the Moon's own actual motion due to its revolution in orbit disregarded, the lunar body would appear to move across the sky in a circle very nearly parallel to the celestial equator.

These small circles in which most celestial objects (other than those located directly on the celestial equator) appear to move, subject only to the diurnal rotation of the Earth, are called parallels of declination. Great circles perpendicular to the plane of the celestial equator, spaced 1 hour apart, and passing through the celestial poles, are designated as hour circles. That hour circle which coincides with the vertical circle of the horizon system of coordinates, and passes through the zenith, nadir, north and south celestial poles, as well as the north and south points on the horizon, is termed the meridian.

And it is here that the first distinction is found affecting the motions of relatively close astronomical bodies such as the Moon and Sun, because of the different positions in which these would be seen from the center of the Earth and from its surface. The difference is a direct function of the geocentric parallax. A changing parallax angle of the Moon relative to the Earth occurs as the Moon successively regresses toward, transits, and falls behind the meridian due to the Earth's faster rotation in the same direction as that of the Moon's orbital revolution.

At any particular latitude of observation on the Earth's surface, a greater distance is involved in the side of the parallax triangle joining the Moon and an observing position on the far side of the meridian than in the case of an observing position on its near side. When the Moon is west of the meridian, the effect of parallax is, therefore, to increase the hour angle; when the Moon is east of the meridian, the effect of parallax is to reduce the hour angle.

The coordinate of right ascension is measured in the plane of the celestial equator and, although it is subject to geocentric and topocentric differences in the same manner as the hour angle, the right ascension of a body does not vary with the geographic longitude of the observing position on Earth, while the hour angle of the object does. Because the change in parallax with position in hour angle is different from the change of parallax with right ascension, the diurnal motions in hour angle and in right ascension of a close celestial body are not the same. The difference is of some consequence in the case of the Moon, whose apparent motion results from a combination of the Earth's diurnal motion and the Moon's own orbital motion.

Whereas any change in the Moon's position caused by the diurnal rotation of the Earth alone would occur in a path which, over a short period of time, would remain parallel to the celestial equator, the lunar body actually appears to move along a track on the celestial sphere which is a composite of the Moon's own orbital path and the diurnal circle produced by the Earth's rotation. It is often found to be more convenient to measure such apparent motion by means of an available alternate in the equatorial coordinate system. This variation employs the celestial meridian rather than the vernal equinox as a point of reference and thereby becomes more meaningful in establishing the effects, upon motion in right ascension, of topocentric position on the Earth. The corresponding adaptation of the equatorial system is termed the hour-angle subsystem. That component of the Moon's apparent movement which is parallel to a declination circle and takes place between successive hour circles or fractional parts thereof in a standard unit of time is termed, in the discussion which follows, the rate of change in hour angle. The specification of apparent motion in either geocentric or topocentric systems is denoted by adding a subscript "*G*" or "*T*," respectively.

The value of the mean diurnal geocentric motion of the Moon in hour angle *h* and time *t*, resulting from the rotation of the Earth, is given by the differential function

$$\left[\frac{dh}{dt}\right]_G = 15.04100^{\circ/h}$$

This figure is derived by a transformation from time to angular systems of measurement. It represents the slight excess ($3{,}609.856473^s$) over the length of the mean solar hour (i.e., $1^h = 60^m \times 60^s = 3{,}600^s \times 1.003$) resulting from an average decrease, by atmospheric refraction, of the rate of change in hour angle. The corresponding value when converted into radian measure is

$$\left[\frac{dh}{dt}\right]_G = 0.26252^{\mathrm{rad/h}}$$

Similarly, the value of the mean diurnal topocentric motion of the Moon in hour angle, exclusive of the Moon's own orbital motion, is

$$\left[\frac{dh}{dt}\right]_T = 14.49208^{\circ/h}$$

which is equivalent to

$$\left[\frac{dh}{dt}\right]_T = 0.25294^{\mathrm{rad/h}}.$$

It will be seen that when the next-to-the-last value is multiplied by $24^{h/d}$, giving 347.808°, it is less than the 360° defining one rotation of the Earth, since it contains the effects of the Moon's eastward drift resulting from the Earth's orbital revolution described a few sections earlier. If the additional 50.415^{m} (0.84025^{h}) of the mean daily lunar retardation (see pt. II, ch. 2) is multiplied by the same rate of lunar motion, it gives 12.177°, and if this is added to the rotation during 24^{h}, the full 360° comprising the daily angular rotation of the Earth from one lunar transit to the next is obtained.

Substituting these quantities (in radian measure) in the second of the preceding equations:

$$\begin{aligned}\Delta\alpha \text{ (geocentric)} &= 0.26252^{\mathrm{rad/h}} - 0.25924^{\mathrm{rad/h}} \\ &= 0.00958^{\mathrm{rad/h}};\ 0.00958^{\mathrm{rad/h}}/0.01745^{\mathrm{rad/°}} \\ &= 0.54900^{°/\mathrm{h}} = 134.7^{\mathrm{s/h}}.\end{aligned}$$

Assuming, by way of example, that the Moon is on the celestial equator ($\delta=0°$) and is just transiting the local meridian ($h=0°$) at the latitude of the U.S. Naval Observatory in Washington, D.C. ($\phi = 38°55'14.0''$ N.) and, for simplicity, that $\pi = 60' = 3{,}600''$.

Then:

$$\Delta\alpha = 134.7^{\mathrm{s/h}} + \frac{3600'' \cos 38°55'14.0'' \cos 0°}{57.3^{°/\mathrm{rad}} \cos 0°}$$

$$= 134.7^{\mathrm{s/h}} + \frac{2{,}800.9}{57.3} = 183.6^{\mathrm{s/h}}.$$

The effect of the Moon's additional component of motion in right ascension resulting from its own orbital motion will be discussed in connection with the extreme lunar displacement caused by the lunar nodical cycle, as shown in fig. 36 (pt. II, ch. 4).

The Relationship of the Moon's Motion in Right Ascension to Its Declination

In the basic equation evaluated above, involving only the effect of the Earth's diurnal rotation upon the change in right ascension of the Moon, it will be observed that the cosine of the declination occurs in the denominator. Hence, as the declination increases from 0° to 90°, the influence of this factor upon the change in right ascension varies from (1) the minimum value produced by the other parameters h, π, and ϕ, through (2) larger values introduced by the presence of a decimal fraction in the denominator, to (3) infinity at 90° (any motion in right ascension is indeterminate at the celestial poles).

From an analysis of the spherical trigonometry relationships in figure 25B, it is also obvious that the apparent motion of the Moon along any portion of a parallel circle of declination (whose radius must decrease toward the poles) will likewise vary from a maximum on the celestial equator to zero at the poles. That is, the apparent change in right ascension $(\Delta\alpha)_P$, along any parallel circle will, as caused by the Earth's diurnal rotation alone, be approximately equivalent to the change in right ascension at the equator $(\Delta\alpha)_E$, multiplied by the cosine of the declination of the Moon (i.e., $(\Delta\alpha)_P = (\Delta\alpha)_E \cos \delta$).

At the Equator, *all* of the Moon's apparent diurnal motion occurs in the coordinate of right ascension, and hence the length of the lunar day is increased a greater amount.

The precise relationships which variously modified lunar motions in right ascension have with respect to the Moon's declination actually are quite complex. Furthermore, the significance of the declination-induced magnitudes of these *apparent* motions in right ascension resulting from the Earth's diurnal rotation as they influence the tide-raising potential should not be confused with other effects associated with the Moon's own orbital motion. Those purely dynamic aspects of the tide-raising forces which are related to lunar declination will be described in part II, chapter 4.

Chapter 2.

Factors Affecting the Magnitude and Duration of the Tide-Raising Forces

The preceding chapter describes the continuously changing positions and motions of the Moon, Earth, and Sun which, taken together, result in correspondingly varying astronomical forces responsible for the production of the tides. In the present chapter, attention will be focused upon certain closely related factors operating to increase both the magnitude and duration of these tide-raising influences.

Principal Effects

Various alignments and combinations of the gravitational forces acting, as well as the relative distances between Earth, Moon, and Sun, and the angular positioning of the latter two bodies with respect to any observing position on the Earth's surface, collectively exercise a very important influence in producing tides of considerably increased amplitude and/or range. Similarly, the relative speeds of motion of these same three bodies, the inclinations of the apparent paths of the Moon and Sun to the celestial equator, and the lengths of their arcs of movement across the sky, affect the period of time during which such augmented tides exist.

In general, the enhanced astronomical forces creating perigean spring tides are of relatively short duration. Plots of these tides are marked by more steeply sloping curves of tidal growth and decline (see part II, chapter 8) associated with the transient reinforcement of the tidal forces. These amplified crests and troughs occur at appropriate times of high and low water during the tidal day. As a result, a very important factor of determination in connection with the relative intensity of perigean spring tides involves the changing lengths of the tidal day within which such transitorily increased tidal forces are exerted.

Two important concepts affecting the duration of the tidal forces acting which will appear repeatedly in future analytic discussions throughout the text are those of (1) lunar transit times, and (2) the necessary "catch-up" times between a point on the rotating Earth and various apparent motions of both the Moon and Sun in the same direction. Other dynamic factors of consequence to the period of application of augmented gravitational forces involve the instantaneous geometric figure and varying rotational motion of the orbit of the Moon. These are both subject to small disturbances known as "perturbations" caused by the changing gravitational attraction of the Sun, and such perturbations may, in turn, give rise to corresponding variations in the length of the tidal day.

The perturbations produced in the lunar orbit will form one of the principal topics for discussion in part II, chapter 3, and the further description of their associated effects will be reserved until then. However, with consideration to the duration of time in which augmented tide-raising forces can act, it is desirable to provide an immediate introduction to the close connection between lunar transit times and the length of the *lunar day* (as loosely designated, before various modifications and differences indicated in the present chapter cause it to become the *tidal day*). Significantly, certain changes in the length of the tidal day may also cause variations in the catch-up times of the rotating Earth.

Foremost among the variable quantities affecting the length of the lunar day and, through it, the tidal day, is the *daily lunar retardation*. The actual magnitude of the daily lunar retardation also bears a very close relationship to the daily differences in motion of the Moon in right ascension, introduced in the preceding chapter and continued in the present one.

The Daily Lunar Retardation

As has been previously noted, the period of revolution of the Moon in its orbit around the Earth from conjunction or alignment with a star to conjunction with that same star again is known as the *sidereal month.* Its *mean* value is 27.321661 days. This figure represents the average period of revolution, obtained from the individual, real motion of the Moon in space. It is independent of either the Moon's combined revolution with the Earth around the Sun (annual orbital motion) or the rotation of the Earth on its axis (diurnal motion) which causes the Moon to rise and set, and to move daily across the sky with respect to any location except one in extreme polar latitudes on the surface of the Earth. Both of the motions named above in parentheses, and others as well, do, however, introduce modifications in the apparent speed of movement of the Moon. Through corresponding alterations in the length of the lunar day, they also affect the length of the tidal day and, with this, the magnitude of the tides.

Thus, continuing from the sidereal or true month, the average period of time between two successive conjunctions (or oppositions) of the Moon with the Sun (i.e., at new moon or full moon, respectively) is termed the synodic month. Because the Earth's own mean (orbital) motion around the Sun carries the Moon with it approximately 0.985647° eastward each day and this same amount farther away from the next succeeding alignment between Earth, Moon, and Sun at time of syzygy, a necessary catch-up motion is required. The synodic month is, therefore, 2.208928 days longer than the sidereal month, or 29.530589 days.

In the following equation M_{sid} = the length of the sidereal month, in mean solar days (measured by the revolution of the Moon through 360° from alignment with one star to alignment with that same star again). In one day, the Moon will, therefore, move through $360°/M_{sid}$. Similarly, Y_{sid}= the length of the ordinary (sidereal) year, in mean solar days. In one day, the Earth will move through $360°/Y_{sid}$. As the Earth revolves in its annual orbit around the Sun, the Sun appears to move forward in the same direction in the sky. Accordingly, the quantity $360°/Y_{sid}$ also represents the *apparent* daily motion of the Sun, caused by the Earth's revolution.

Since the average (mean) orbital motion of the Moon is 12.190749°/day and the mean apparent motion of the Sun (the equivalent of the Earth's mean orbital motion) is only 0.985647°/day, the Moon appears to move much faster in its daily eastward motion in the sky than does the Sun. (This motion is not to be confused with the daily rising and setting motions of both the Sun and Moon in a westward direction across the sky, an apparent motion caused by the oppositely directed rotation of the Earth.) In its fictitious eastward motion with respect to the Earth, the Sun *appears* to be moving in the same direction in which the Moon actually revolves around the Earth. Thus, the Moon must, during each month, catch up with the current position of the Sun to achieve a direct alignment between Earth, Moon, and Sun at times of either new moon or full moon.

The mean period of time, in days, between two such successive occurrences of either new moon or full moon has been defined as the synodic month (M_{syn}).

The mean daily gain of the Moon on the Sun is given by the equation:

$$360°/M_{sid} - 360°/Y_{sid} = 360°/M_{syn}.$$

Therefore $1/M_{syn} = 1/27.321661 - 1/365.25636042$
$= 0.036600996 - 0.002737803$
$= 0.033863193$

or $M_{syn} = 29.530589$ days.

With respect to the Sun, the Moon advances in one mean solar day through the previously mentioned average angular distance of $360°/29.530589^d = 12.190749°$. In terms of its times of transiting the celestial meridian, the Moon is retarded daily through this angle, on the average, throughout the year. Because the apparent angular motion of the mean sun is only 0.985647°/day and that of the Moon with respect to the Sun many times greater, the Moon is constantly gaining on, and passing the Sun.

At the same time that the Moon and the Earth are revolving in their separate orbits, at mean angular velocities of 0.549°/mean solar hour and $0.041°/^{msh}$, respectively, the Earth is rotating on its axis and at a very much faster angular rate given by $360°/24^h = 15.0°/^{msh}$. In contrast with the Earth's revolutionary motion around the Sun, this results in an apparent motion of the Sun in a direction opposite to that in which the Earth is rotating. Accordingly, as a reflection of the Earth's daily axial rotation, but subject to a small eastward component of motion equal to the daily portion of the Earth's eastward revolution around the Sun, the Sun appears to move westward in the sky and transits the upper meridian of any place once each apparent solar day. The period of time between two successive transits of the true Sun is extremely variable throughout the year. However, at a very early time, this apparent motion of the true Sun became the basis for timekeeping by means of sundials.

Later, for purpose of convenience, the motion of an hypothetical or fictitious mean sun was chosen, and this concept has persisted, although the method of determining extremely precise clock time has changed. The mean sun is assumed to move uniformly with a constant, average rate of motion along the celestial equator instead of along its apparent true path, the ecliptic—and without any variation due to the Earth's changing velocity in orbit around the Sun. The time between two successive upper transits of this mean sun across the local meridian of any place is defined as the *mean solar day* of 24 mean solar hours.

1. The Lunar Day

The Moon is likewise caused to transit the upper meridian of any place on the Earth's surface once each day as a result of the Earth's axial rotation. However, the Moon is revolving in its orbit in the same direction as that in which the Earth is rotating on its axis, and this results in an extra amount of time required for a position on the Earth's surface, subject to its rotational motion, to catch up with the Moon's changing position. In relating the daily apparent gain in position of the Moon to the correspondingly delayed time at which the Moon reaches the upper meridian of a place, and hence the amount of this delay, the following reduction is used:

Daily mean synodic motion of the Moon in orbit $=12.190749°$.

Mean solar day = 24 mean solar hours.

Thus, the mean synodic motion of the Moon per hour is

$$12.190749° \text{ per day}/24 \text{ hours per day}$$
$$=0.507948° \text{ per mean solar hour.}$$

Since the Earth rotates through 15° in one mean solar hour, the preceding hourly motion of the Moon in its orbit (or, when the Moon is on the celestial equator, the instantaneous motion in right ascension) involves a time-delay factor of:

$$=0.507948° \text{ per mean solar hour.}$$
$$=0.033863 \times 60 \text{ minutes/hour} \times 24 \text{ hours/day}$$
$$=48.73008 \text{ minutes} = 48^m 45.8^s.$$

However, as the Earth rotates through 360° on its axis, the Moon moves through 12.190749° in its own orbit around the Earth. Allowing for this catch-up motion of the Earth's rotation upon the changing position of the Moon, the average daily delay between two successive transits of the Moon across the celestial meridian of a place on the Earth's Equator is

$$360°+12.190749°=372.190749°$$
$$48.762996^m \times 372.190749°/360°=50.414267^m$$
$$=50^m\ 24.9^s.$$

Since the lunar day is defined as the period of time between two successive upper transits of the Moon across the local meridian, the length of the *mean lunar* day at the Equator is, therefore, $24^h\ 50^m\ 24.9^s$. The amount above 24 hours is known as the *mean daily lunar retardation.*

2. The Tidal Day

It must be noted that the angular velocity of the Moon from which the above value of the mean lunar day is derived is steadily changing. These changes are caused by the elliptical shape of the Moon's orbit, its inclination to the celestial equator—with consequent continuously varying declinations—and by perturbations produced within the lunar orbit. Other local fluctuations in the Moon's apparent angular velocity across the sky result from the latitude of the position of observation and the Moon's varying zenith distance. The average value of the daily lunar retardation in transit times may, accordingly, range from 38 to 66 minutes, but may be quite different from the corresponding retardation times in the Moon's rising or setting. Various factors—notably the seasonal changes in the inclination of the ecliptic to the celestial equator and the continuously varying angle between the Moon's orbit and the local horizon—cause the lunar retardation times in these respective positions to be different. Similarly, only in transiting the meridian are the Moon's angular motions in right ascension, hour angle, and azimuth the same. At increasingly larger angles from the meridian, greater divergences appear among these three motions.

The mean lunar day has been defined above. For certain general purposes, and where only average values are concerned, the mean tidal day may be regarded as synonymous with, and equivalent in length to, the mean lunar day. This does not apply where considerable deviations in the length of the tidal day, dependent upon tidal responses to reinforcing astronomical conditions, are a matter of immediate concern.

By contrast, a more exacting interpretation of the actual tidal day (see appendix, fig. 6), as used generally throughout this volume, involves the period of time between the larger maxima (or minima) of two tides of the same type (ordinarily measured between one higher high water and the next).

The differences between any specific lunar day and the corresponding tidal day are obvious: Lunar transit times used in the determination of the lunar day consider only the instant of passage of the Moon across the upper or lower branch of the meridian, and are, therefore, restricted to the meridian altitude of the Moon [a]; large numbers of intermediate occurrences of tidal peaks, with the Moon being at different altitudes and azimuths, would not be included under this definition of the tidal day, since the times of lunar transit and those of the maximum rise of the tide do not bear a one-to-one correlation. Moreover, the length of the tidal day as used in the second and more restrictive sense involves numerous additional variable quantities. These are associated with the relative positions, motions, and forces of both the Moon and Sun, perturbations of the Moon's orbit by the Sun, and other specific circumstances relating both to hydrography and dynamic oceanography. (See pt. II, chs. 4, 6.) This more exact usage is especially applicable in the comparison of tidal actions at localized observing stations which are subject to (1) different high-water lunitidal intervals (i.e., specific time intervals between lunar transit and the highest rise of the tide, attributable to hydrographic and other causes), and (2) varying delays in attaining a maximum tide rise after transit of the Moon (associated with unequal phase and parallax lags at the individual stations). These effects are discussed further in part II, chapter 6.

Relationship of the Tidal Day to Lunar Transit Times, Hourly Differences in Right Ascension of the Moon, and Other Factors

A comparison of data tabulated in *The American Ephemeris and Nautical Almanac* shows that the greatest difference in time between successive upper and lower transits of the Moon occurs when the difference between successive hourly right ascensions also reaches a maximum value (i.e., the Moon is moving eastward in right ascension by its greatest amount). The agreement between these two factors is very close. An increase in the differences between the values of hourly right ascension and an increase in the differences between the retardation times affecting the transit of the Moon are, in fact, directly correlatable.

Conversely, the least difference in time between immediately succeeding upper and lower transits (or two succeeding upper transits) of the Moon occurs when the difference between successive hourly right ascensions attains a minimum value. Other possible correlations, particularly any sought between the motions of the Moon in either right ascension or declination and the corresponding length of the tidal day (as distinct from the lunar day) are not as well defined.

The greatest and least values of the hourly differences in right ascension usually occur, in a directly opposite relationship, at times very close to those of the least and greatest values, respectively, of hourly change in declination. However (since other factors also affect the two coordinates), these opposing maximum and minimum values of hourly change in right ascension and declination do not necessarily occur even on exactly the same day. Similarly, the time of maximum retardation in transit of the Moon does not necessarily agree exactly with an increase in the length of the tidal day as defined in the second concept given above and determined from tide tables. This is because various other astronomical circumstances, including the gravitational influence of the Sun, are also effective in altering the period of time between successive high waters, and hence the length of the tidal day.

Among those circumstances which tend to *increase* the Moon's apparent motion in right ascension as seen from the Earth are: (1) proximity of the Moon to the position of perigee-syzygy, causing an acceleration of the Moon's direct motion in orbit; and (2) proximity of the Moon to its largest values in declination, positive or negative, resulting in a maximum forward motion in right ascension.

Circumstances which tend to *decrease* the Moon's apparent motion in right ascension include: (1) proximity of the Moon to the position of apogee-syzygy, with the decreased gravitational force of the Earth causing a reduction in the Moon's forward velocity in orbit; and (2) creation of the maximum possible angle of inclination between lunar orbit and the celestial equator ($\pm 28.5°$) during the appropriate phase of the 18.6-year lunar nodical cycle (pt. II, ch. 4), thus markedly increasing the inclination of the Moon's topocentric path in declination, augmenting its apparent motion in this coordinate and, to a certain extent, decreasing its apparent motion in right ascension; this effect is in addition to the greater inclination between the declinational motion of the Moon and the celestial equator, and the relatively reduced motion in right ascension which occurs when the Moon is near to, or crossing, the celestial equator compared to that when it is near its semimonthly position of maximum declination.

[a] It should be noted at this point also that a small distinction exists between the meanings of "culmination" and "meridian transit" due to variations between the angles at which parallels of declination (equatorial system) and almucantars (horizon system) cross the celestial meridian. Thus the Moon may transit the meridian, yet not be exactly at its maximum angular altitude above the horizon, as implied by the word "culmination." In the Northern Hemisphere, as the Moon moves toward greater declinations, it culminates following its transit of the meridian.

Apparent Diurnal Motion of a Body "Fixed" in Space

When a very distant and hence, in terms of its actual space motion, essentially stationary celestial object such as a star is subject to the Earth's diurnal rotation, it will apparently move through the same distance in hour angle in the same period of time, no matter at what declination it is situated. The reason is a geometric one. Although hour circles converge toward the poles, a point on any given hour circle is located exactly one hour in time from its counterpart position (i.e., one located at the same declination) on an immediately adjacent hour circle. In viewing, from a suitable position on the surface of the Earth, any such celestial objects having declinations ranging from 0° to 90°, those objects located at greater declinations will *appear* to move more slowly (in linear velocity) across the celestial sphere than those on or near the celestial equator, but their angular velocities are the same.

Apparent Diurnal Motion of a Body Possessing Its Own Motion in Right Ascension

In the case of a relatively nearby celestial object such as the Moon, which also possesses its own orbital motion, positional displacements result that are quite different from those of the preceding section. Where, as in the example of the actual motion of the Moon and the apparent motion of the Sun, the movement of these bodies is in the same direction as that of the Earth's rotation (i.e., a direction eastward, or counterclockwise as viewed from the respective poles of revolution and rotation), a special catch-up motion is involved which will be extensively discussed in subsequent chapters. (The only exceptions to this statement occur in the cases of a few asteroids and comets that revolve around the Sun in a retrograde direction, as well as those planets of the solar system that are relatively close to the Earth and may, on occasion, exhibit apparent retrograde motions.)

Following upon the meridian transit of a celestial body having its own direct motion, as observed from a particular location on the Earth's surface, the Earth must rotate through more than one complete rotation to bring this body into direct alignment over this same point on its surface again.

Any nonpolar point on Earth rotates in a plane either in, or parallel to, the celestial equator. In considering the motion of any other body relative to this plane, the body's apparent daily displacement must be converted to an equivalent component of motion in the equatorial plane. Unless the body remains in the plane of, or parallel to, the celestial equator (i.e., exhibits motion only in a diurnal circle) during the entire period of one rotation of the Earth, as in the case of a "fixed" star, a trigonometric reduction is necessary to obtain the object's individual motion in, or parallel to, the celestial equator. Although the Sun is a star, its distance from the Earth is relatively so close that it also exhibits the simulation of the Earth's annual orbital motion previously described.

Only for a short period of time around the equinoxes where the ecliptic crosses the celestial equator and the Sun's declination is zero is its motion in longitude very nearly equal to its motion in right ascension. Hence, only in these positions is the Sun's westerly displacement in hour angle (caused by the Earth's diurnal rotation) in the same plane as the Sun's easterly motion in longitude, produced by the Earth's annual revolution. At all other times and positions, the daily angular difference in the Sun's longitude must be converted to a corresponding daily motion in right ascension by the use of transformation equations or, more simply, can be obtained directly from tables of right ascension of the Sun. The tabulated daily difference in the Sun's apparent motion in right ascension (caused by the annual revolution of the Earth) is then subtracted from the oppositely directed component of apparent motion in hour angle, measured in the same equatorial plane, and caused by the diurnal rotation of the Earth. The resulting difference indicates the necessary additional time required for a given point on the Earth's surface to catch up to a position of alignment with (i.e., a meridian transit of) the Sun.

Similarly, except at the two positions each month where the Moon crosses the Earth's Equator, the changing lunar longitudes must be converted to a daily difference in right ascension, or the necessary equatorial coordinate values can be obtained from tables of lunar right ascension. The daily difference in right ascension caused by the Moon's motion in orbit is then subtracted from the amount of the Moon's motion in hour angle produced by the Earth's rotation to determine the necessary catch-up time for a given point on the Earth to regain a meridian transit position with the Moon. The principle of this catch-up time will be extensively elaborated upon in the next chapter.

Variations in the Tide-Raising Force Associated With Lunar Parallax

It has been specified previously that, in accordance with Sir Isaac Newton's Universal Law of Gravitation, the gravitational attraction between two celestial bodies varies directly as the product of their masses and inversely as the square of the distance between them (i.e., the closer the two bodies are to each other the greater is the interacting gravitational force; as they draw farther apart, this force decreases as the second power of the distance separating them. However, as noted in the appendix ("The Effect of Gravitational Force"), tide-raising forces vary inversely as the *third power* of the distance.

In the motion of the Moon in its orbit around the Earth, the gravitational force of the Earth is at all times directed at right angles to the lunar orbit, causing the Moon to fall constantly toward the Earth. However, an equal and oppositely directed centrifugal force resulting from the revolution of the Moon in orbit resists the infalling motion and keeps the Moon from plunging toward the Earth. Although the Moon's own gravitational force upon the Earth is directed along a line connecting their centers, two components of this total force exerted upon the Earth's surface, and known as the horizontal (or tractive) component and the vertical component, respectively, act to produce tides in the Earth's waters.

Variations in the Moon's tide-raising force as a result of its changing distances from the Earth form the basis for the phenomenon of *parallactic inequality.*

Because the Moon revolves in an elliptical orbit around the Earth with the Earth located at one focus of the ellipse (fig. 23), once each lunar month the Moon comes to its closest approach to the Earth at perigee and, approximately 2 weeks later, reaches its greatest monthly distance from the Earth at apogee.

As was seen in connection with the earlier discussion of Kepler's Second Law of Planetary Motions, the radius vector—or center-to-center axis joining the Moon and the Earth—sweeps out equal areas at any portion of the lunar orbit within equal intervals of time (fig. 24). The lunar distances delineated by the two sides of the elliptical sector so formed are continuously varying. In order that the radius vector may describe equal areas in the same period of time, the angular velocity of the Moon also must be variable at different portions of the orbit.

In that half of the lunar orbit between apogee and perigee, as the Moon nears its position of closest monthly approach to the Earth, it speeds up in response to the increased gravitational force of the Earth which results from the diminished lunar distance. Conversely, between perigee and apogee, the Moon's angular velocity becomes less. Near the exact position of perigee, the Moon is moving at its maximum angular velocity; at apogee, it is moving the slowest. Each of these latter two positions in the lunar orbit is called an *apse,* and the axis connecting them is correspondingly termed the *line of apsides.*

The changing distance of the Moon from the Earth is measured by the angle subtended by the equatorial semidiameter of the Earth as it would be seen from the Moon—thus in a position very nearly on the local horizon.[b] This is equivalent to the angle (viewed at the center of gravity of the Moon) between a line drawn from the center of the Moon to a semidiametrical position on the surface of the Earth and another line drawn from the center of the Moon to the center of the Earth (fig. 41). It is also equal to the apparent angular difference in the Moon's direction in the sky as it would be seen from these two positions on the Earth. This angle—larger when the Moon is closer and smaller when it is farther away—is termed the *equatorial geocentric horizontal parallax.* Hence, the effect of the changing distances of the Moon in altering the tides, as well as in producing variations in the daily retardation of the tidal day from this cause, is termed the *parallactic inequality.*

Table 8 shows a comparison between the continuously varying values of the geocentric horizontal parallax (π) and the distance (ρ, in Earth-radii) of the Moon from the center of the Earth during an ordinary lunation in the year 1974 (i.e., a period of one synodic month including all lunar phases, but containing no close perigee-syzygy alignment). These data may be contrasted with the data of table 15, which show the values of ρ for various alignments of perigee-syzygy, perigee-quadrature, and apogee-syzygy during 1973 and 1974. The geocentric distance ρ is related to the value of the geocentric horizontal parallax π through the relationship $\rho = \text{cosec}\ \pi = 1/\sin\ \pi$.

TABLE 8.—*Comparison of Geocentric Horizontal Parallax and True Geocentric Distance of the Moon for a Case of Widely Separated Perigee-Syzygy*

Date 1974	Horizontal Parallax		True distance, Earth-radii
	′	″	
Apr. 14.0	54	19.3409	63.286 841
14.5	54	15.9150	63.353 427
15.0	54	15.1045	63.369 201
15.5	54	16.9068	63.334 137
16.0	54	21.2810	63.249 196
16.5	54	28.1483	63.116 302
17.0	54	37.3921	62.938 300
17.5	54	48.8577	62.718 903
18.0	55	02.3534	62.462 612

[b] Where a semidiameter of the Earth perpendicular to any local horizon is considered, a variation in geocentric parallax occurs with altitude of the Moon above the horizon. This "parallax in altitude" is zero in the zenith and maximum on the horizon. Because the Earth is neither a true sphere nor an oblate spheroid (possessing an irregular figure known as a *geoid*), for astronomical purposes the equatorial semidiameter is chosen and adjustments are made, as necessary, for the Moon's altitude and the latitude of observation.

TABLE 8.—*Comparison of Geocentric Horizontal Parallax and True Geocentric Distance of the Moon for a Case of Widely Separated Perigee-Syzygy*—Continued

Date 1974	Horizontal Parallax ′ ″	True distance, Earth-radii
Apr. 18.5	55 17.6508	62.174 627
19.0	55 34.4869	61.860 729
19.5	55 52.5668	61.527 153
20.0	56 11.5681	61.180 433
20.5	56 31.1469	60.827.238
21.0	56 50.9457	60.474 199
21.5	57 10.6026	60.127 721
22.0	57 29.7624	59.793 806
22.5	57 48.0878	59.477 884
23.0	58 05.2716	59.184 663
23.5	58 21.0468	58.918 010
24.0	58 35.1964	58.680 873
24.5	58 47.5589	58.475 242
25.0	58 58.0316	58.302 170
25.5	59 06.5696	58.161 827
26.0	59 13.1813	58.053 612
26.5	59 17.9206	57.976 289
27.0	59 20.8770	57.928 159
27.5	59 22.1638	57.907 235
28.0	59 21.9064	57.911 420
28.5	59 20.2310	57.938 670
29.0	59 17.2549	57.987 138
29.5	59 13.0796	58.055 274
30.0	59 07.7856	58.141 895
30.5	59 01.4311	58.246 210
May 1.0	58 54.0530	58.367 799
1.5	58 45.6704	58.506 561
2.0	58 36.2901	58.662 622
2.5	58 25.9142	58.836 220
3.0	58 14.5475	59.027 578
3.5	58 02.2061	59.236 760
4.0	57 48.9244	59.463 541
4.5	57 34.7619	59.707 284
5.0	57 19.8070	59.966 844
5.5	57 04.1801	60.240 488
6.0	56 48.0338	60.525 864
6.5	56 31.5511	60.819 988
7.0	56 14.9420	61.119 275
7.5	55 58.4383	61.419 595
8.0	55 42.2877	61.716 360
8.5	55 26.7474	62.004 632
9.0	55 12.0776	62.279 239
9.5	54 58.5348	62.534 916
10.0	54 46.3669	62.766 435
10.5	54 35.8074	62.968 744
11.0	54 27.0717	63.137 100
11.5	54 20.3533	63.267 191
12.0	54 15.8210	63.355 255
12.5	54 13.6163	63.398 183
13.0	54 13.8510	63.393 611
13.5	54 16.6051	63.340 003
14.0	54 21.9245	63.236 719

It is also important to note that, because the Moon is bound gravitationally to the Earth, when the Earth is at perihelion and closest to the Sun in its annual motion, the Moon is also nearly so, and is then subject to the maximum gravitational influence of the Sun, including those forces producing perturbations in the lunar orbit. This relationship is, therefore, often referred to as solar perigee (i.e., the Sun reaches a position near solar perigee or apogee as the Earth reaches its position of perihelion or aphelion, respectively).[c]

In order quantitatively to illustrate these combined lunisolar effects, the next-to-the-last column in table 9 shows the relative geocentric distances of the Sun from the Earth corresponding to an astronomical circumstance chosen to accord with the close perigee-syzygy of 1974 January 8. The values are expressed in terms of the mean distance of the Sun from the Earth (equal to the semi-major axis of the Earth's orbit) considered as unity.

The Effect of the Parallax Inequality Upon the Comparative Lengths of the Tidal Day

The average speed of the Moon in its orbit is about 12.2°/day. However, for the reasons given in the previous section and as partly evident in tables 10, 20, the lunar angular velocity increases to an extreme maximum of approximately 14.2° − 15.4°/day [d] at very close perigee-syzygies, diminishes to about 14.1°–14.2°/day at perigee-quadrature, and to 11.8°–12.0°/day at apogee-syzygy or apogee-quadrature. Sensible differences are introduced both in the daily lunar retardation and in the length of the tidal day as the result of these changing lunar velocities.

An interesting comparison can be made between the considerably increased daily lunar retardation produced as the result of such accelerated lunar velocities at the time of perigee-syzygy and the lesser retardation produced subject to the previously computed mean orbital velocity of the Moon (pt. II, ch. 2, "The Daily Lunar Retardation").

Using the same calculation procedure as in the earlier example, involving the mean synodic motion of the Moon:

Maximum daily angular velocity of the Moon in orbit (at the representative close perigee-syzygies of May 2.5 and Nov. 10.5, 1950) = 15.28°/day.

[c] However, the fact that the Earth is at perihelion does not necessarily imply that the Moon is at its absolute minimum distance from the Sun. In order for this condition to be achieved rigorously, the Moon must also be located at its position of apogee (with respect to the Earth) at this time. See chapter 5.

[d] At an occurrence of proxigee-syzygy having a mean epoch of 1918 March 12.39 G.m.t. ($P-S=+29^h$, $\delta=1.56°$, $\pi_{max}=61'27.08''$), the Moon's average daily motion between March 12.0–13.0 was 15.3566°.

TABLE 9.—*The Changing True Distance of the Earth From the Sun (Expressed as a Decimal Portion of the Mean Astronomical Distance of the Earth From the Sun—i.e., the Length of the Semimajor Axis of the Earth's Orbit—Considered as Unity)*

These distances are chosen to accord with the period of time around the close perigee-syzygy alignment of 1974 January 8, and indicate the Earth's least annual distance from the Sun at perihelion on 1974 January 4. The table also shows the corresponding increase in solar semidiameter at perihelion, together with the effect of the Sun's slow daily change in declination and rapid change in right ascension at the winter solstice (1973 December 22).

Date	Apparent right ascension		Apparent declination		True distance of the Earth from the Sun		Semi-diameter
1973	h m s	Δ^s	° ′ ″	Δ″	(a.u.=1)	Δ	′ ″
Dec. 20	17 51 05.47		23 25 37.0		.983 8173		16 16.99
		266.41		42.4		652	
21	17 55 31.88		—23 26 19.4		0.983 7521		16 17.06
		266.50		— 14.2		−614	
22	17 59 58.38		23 26 33.6		.983 6907		16 17.12
		266.54		+ 14.1		574	
23	18 04 24.92		23 26 19.5		.983 6333		16 17.17
		266.55		42.4		536	
24	18 08 51.47		23 25 37.1		.983 5797		16 17.23
		266.51		70.7		498	
25	18 13 17.98		23 24 26.4		.983 5299		16 17.28
		266.45		98.9		460	
26	18 17 44.43		−23 22 47.5		0.983 4839		16 17.32
		266.33		+127.1		−421	
27	18 22 10.76		23 20 40.4		.983 4418		16 17.36
		266.19		155.1		381	
28	18 26 36.95		23 18 05.3		.983 4037		16 17.40
		266.00		183.3		340	
29	18 31 02.95		23 15 02.0		.983 3697		16 17.44
		265.78		211.2		298	
30	18 35 28.73		23 11 30.8		.983 3399		16 17.46
		265.53		239.0		254	
31	18 39 54.26		−23 07 31.8		0.983 3145		16 17.49
		265.24		+266.8		−208	
1974							
Jan. 1	18 44 19.50		23 03 05.0		.983 2937		16 17.51
		264.92		294.4		158	
2	18 48 44.42		22 58 10.6		.983 2779		16 17.53
		264.57		321.7		107	
3	18 53 08.99		22 52 48.9		.983 2672		16 17.54
		264.18		349.1		− 52	
4	18 57 33.17		22 46 59.8		.983 2620		16 17.54
		263.78		376.1		+ 6	
5	19 01 56.95		−22 40 43.7		0.983 2626		16 17.54
		263.35		+403.1		+ 68	
6	19 06 20.30		22 34 00.6		.983 2694		16 17.53
		262.89		429.8		130	
7	19 10 43.19		22 26 50.8		.983 2824		16 17.52
		262.40		456.2		197	
8	19 15 05.59		22 19 14.6		.983 3021		16 17.50
		261.89		482.6		263	
9	19 19 27.48		22 11 12.0		.983 3284		16 17.48
		261.37		508.6		330	
10	19 23 48.85		−22 02 43.4		0.983 3614		16 17.44
		260.82		+534.5		+396	
11	19 28 09.67		21 53 48.9		.983 4010		16 17.40
		260.25		560.1		460	
12	19 32 29.92		21 44 28.8		.983 4470		16 17.36
		259.66		585.5		519	
13	19 36 49.58		21 34 43.3		.983 4989		16 17.31
		259.06		610.7		577	

TABLE 9.—*The Changing True Distance of the Earth From the Sun etc.*—Continued

Date	Apparent right ascension				Apparent declination				True distance of the Earth from the Sun			Semi-diameter	
1974	h	m	s	Δ^s	°	′	″	Δ''	(a.u.=1)		Δ	′	″
Jan. 14	19	41	08. 64		21	24	32. 6		. 983	5566		16	17. 25
				258. 45				635. 5			631		
15	19	45	27. 09		−21	13	57. 1		0. 983	6197		16	17. 19
				257. 80				+660. 0			+682		
16	19	49	44. 89		21	02	57. 1		. 983	6879		16	17. 12
				257. 15				684. 3			729		
17	19	54	02. 04		20	51	32. 8		. 983	7608		16	17. 05
				256. 47				708. 2			775		
18	19	58	18. 51		20	39	44. 6		. 983	8383		16	16. 97
				255. 77				731. 8			817		
19	20	02	34. 28		20	27	32. 8		. 983	9200		16	16. 89
				255. 07				755. 0			858		
20	20	06	49. 35		−20	14	57. 8		0. 983	0058		16	16. 80

Mean solar day=24 mean solar hours.

Hence, the mean hourly motion of the Moon at its maximum orbital velocity is

$15.28°$ per day/24 hours per day$=0.6367°$ per hour.

Since the Earth rotates through 15° in one hour, this represents a corresponding time delay factor of

$0.6367°$ per hour/$15°$ per hour

$=0.0424\times60$ minutes/hour $\times24$ hours/day

$=61.1232$ minutes$=61^m\ 7.39^s$.

Since the Moon revolves through 15.28° in its own orbit while the Earth rotates through 360° on its axis, the Moon's right ascension increases by this same amount.

$360°+15.28°=375.28°$

$61.1232\times375.28°/360°=63.7175^m=63^m\ 43.0^s$.

Thus, subject to these maximized conditions in the Moon's orbital velocity at the time of a very close perigee-syzygy, the actual daily lunar retardation has increased from its mean value of $50^m\ 24.9^s$ to $63^m\ 43.0^s$, a gain of more than 13 minutes.

The increase in the value of the daily lunar retardation and corresponding extension of the tidal day also result in an increase in the time required for a point on the rotating Earth to catch up with the additional advancement of the Moon in its orbit made possible in this lengthened interval and at the Moon's greater orbital velocity.

As before, the revolution of the Moon around the Earth in the same direction as the Earth rotates on its axis means that, for the Moon to undergo two successive transits over any one location on the Earth's surface (in the first definition of the lunar day) the rotating Earth must catch up through the angle the Moon has moved in the sky during the time the Earth has rotated once through 360° with respect to the Sun (i.e., the mean solar day). As seen earlier, this extra angular distance through which the Moon will have moved eastward across the sky during the lunar day may range from 11.8°–15.4°, depending upon the Moon's position in its orbit.

Although the tides, in general, quite closely follow the motions of the Moon, it will be seen in chapter 6 (cf., "The Phase Age and Parallax Age") that, under certain astronomical and hydrographic situations, their maximum amplitudes may occur either before or after lunar transits. While the time of lunar transit is not, therefore, an accurate indicator of the time of high water, any change which affects the apparent transit time of the Moon will, in one way or another, affect the times of the tides.

When the Moon is traveling faster in its orbit at times of perigee-syzygy, the value of the daily lunar retardation is greater, and the interval required for the Earth's rotation (in the same direction) to catch up with the position of the Moon is longer. The interval between two successive higher high waters (the second definition of the tidal day) is increased in proportion. Conversely, when the Moon's orbital velocity is reduced, as it approaches apogee, the daily lunar retardation is decreased and the tidal day is shortened.

Repeating the previous computations, but substituting the data for a near-minimum velocity of the Moon in orbit (11.82° per day) at a situation of apogee-quadrature on April 13, 1974 gives:

$11.82°$ per day/24 hours per day$=0.4925°$ per hour

$0.4925°$ per hour/$15°$ per hour

$=0.0328\times60$ minutes/hour$\times24$ hours/day

$=47.2320$ minutes$=47^m\ 13.9^s$

$360°+11.82°=371.82°$

$47.2320^m\times371.82°/360°=48.7828^m=48^m\ 47.0^s$.

The effect of parallactic inequality thus results in a difference of more than 15 minutes, on the average, be-

TABLE 10.—*Approximate Orbital Angular Velocity of the Moon, Expressed as a Difference in Celestial Longitude, Showing the Variation at Times of Close Perigee-Syzygy (Proxigee-Syzygy), Apogee-Syzygy (Exogee-Syzygy), and Perigee-Quadrature*

Alignment	Date	Apparent lunar longitude	Average daily motion in longitude
	1974	°	°
	Jan. 1.0	1.2803	
			12.8622
	2.0	14.1425	
			13.2472
	3.0	27.3897	
			13.6763
	4.0	41.0660	
			14.1238
	5.0	55.1898	
			14.5529
	6.0	69.7427	
			14.9174
	7.0	84.6601	
			15.1697
Proxigee-Syzygy	8.0	99.8298	
			15.2705
	9.0	115.1003	
			15.2006
	10.0	130.3009	
			14.9678
	11.0	145.2687	
			14.6046
	12.0	159.8733	
			14.1593
	13.0	174.0326	
			13.6833
	14.0	187.7159	
			13.2216
	15.0	200.9375	
			12.8066
	16.0	213.7441	
			12.4582
	17.0	226.2023	
			12.1847
	18.0	238.3870	
			11.9868
	19.0	250.3738	
			11.8588
	20.0	262.2326	
			11.7929
	21.0	274.0255	
			11.7790
	22.0	285.8045	
			11.8078
Exogee-Syzygy	23.0	297.6123	
			11.8711
	24.0	309.4834	
			11.9631
	25.0	321.4465	
			12.0811
	26.0	333.5276	
			12.2258

Alignment	Date	Apparent lunar longitude	Average daily motion in longitude
	1974	°	°
	Jan. 27.0	345.7534	
			12.4004
	28.0	358.1538	
			12.6104
	29.0	10.7642	
			12.8613
	30.0	23.6255	
			13.1566
	31.0	36.7821	
	Apr. 24.0	53.5013	
			13.9751
	25.0	67.4764	
			14.0916
	26.0	81.5680	
			14.1590
	27.0	95.7270	
			14.1861
	28.0	109.9131	
			14.1813
	29.0	124.0944	
Perigee-Quadrature (1st quarter)			14.1491
	30.0	138.2435	
			14.0889
	May 1.0	152.3324	
			13.9968
	2.0	166.3292	
			13.8668
	3.0	180.1960	
			13.6949
	4.0	193.8909	
	Nov. 2.0	63.1558	
			13.6210
	3.0	76.7768	
			13.7851
	4.0	90.5619	
			13.9238
	5.0	104.4857	
			14.0395
	6.0	118.5252	
			14.1316
	7.0	132.6568	
Perigee-Quadrature (3d quarter)			14.1961
	8.0	146.8529	
			14.2249
	9.0	161.0778	
			14.2076
	10.0	175.2854	
			14.1339
	11.0	189.4193	
			13.9977
	12.0	203.4170	

tween the respective values of the daily tidal retardation as they occur at perigee-syzygy and at either apogee-syzygy or apogee-quadrature. The smaller value of the retardation, occurring at apogee-syzygy, averages about 49 minutes per day.

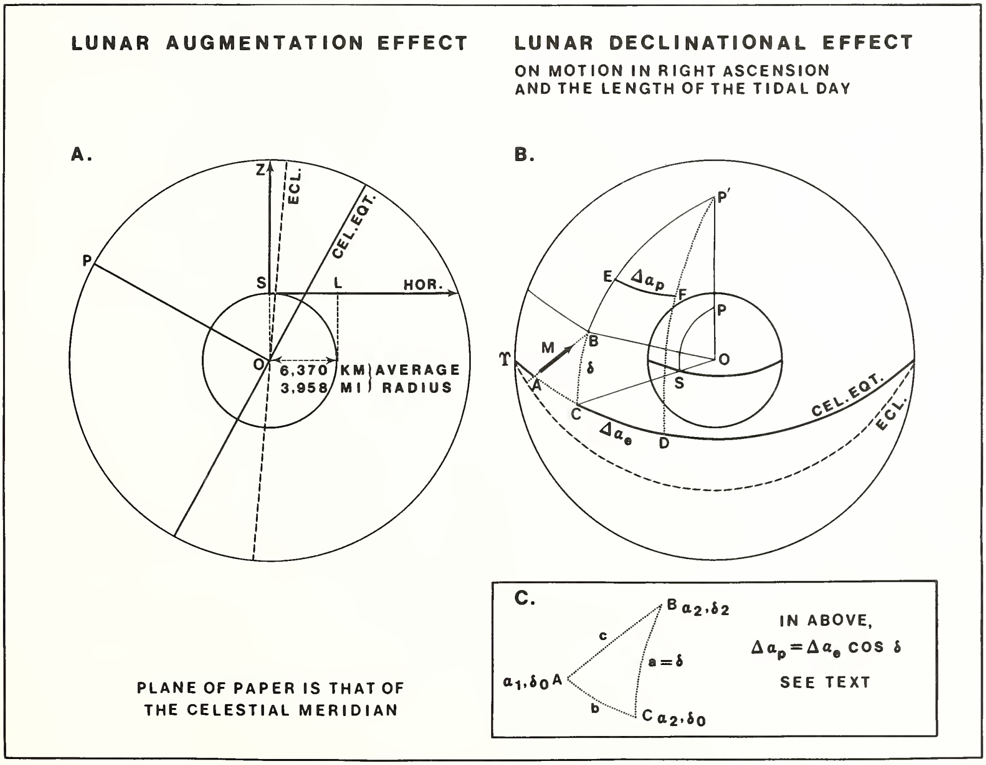
This difference of approximately 15 minutes, permitting a longer application of the combined gravitational forces of the Sun and Moon, and at a time when the latter is exerted from a relatively close distance—together with certain other factors to be developed in ensuing chapters—add measurably to the greater tidal flooding potential at times of perigee-syzygy.

Ancillary Effects

Lunar Augmentation

In figure 25A, which represents the position of the Moon on the celestial sphere as seen in the horizon system of coordinates, it is very obvious that, when the Moon is in the zenith, it is a distance equal to the equatorial radius of the Earth (6,378.388 km or 3,963.530 mi) nearer to the surface of the Earth than when it is on the horizon. This amounts to a gravitationally significant portion (0.017) of the average distance of the Moon from the surface of the Earth (378,000 km or 234,900 mi). Since the tide-raising force increases rapidly as the third power of any diminished distance of the Moon from the Earth, this quantity is of measurable importance in dealing with tidal phenomena. The same geometric principle is true for the Sun-Earth configuration, but the change in distance here represents but an insignificant portion of the mean distance of the Earth from the Sun (149,500,000 km, or 92,900,000 mi).

The effect of the lunar augmentation impacts upon those aspects of tidal prediction which relate to the instantaneous distance of the Moon from the Earth and it can,



Figures 25 A, B

therefore, be considered as a correction to the lunar horizontal parallax. The computation necessary to evaluate the quantitative influence of this phenomenon as it affects the tides follows.

To the second order, neglecting the flattening of the Earth,[e] while assuming that the Earth's semidiameter $r=1$, and that the Moon is transiting the local meridian ($h=0°$), the amount of the augmentation in lunar semidiameter ($S-S_0$) is given approximately by:

$$S-S_0=S_0 \sin H_0 \cos z'+S_0 \sin^2 H_0 \, (1-\tfrac{1}{2} \sin^2 z')$$

where (all values are for the Moon)

- S =the observed (topocentric) angular semidiameter
- S_0 =the geocentric angular semidiameter
- H_0 =the equatorial horizontal parallax
- z' =the topocentric zenith distance (from the geodetic zenith).

From *The American Ephemeris and Nautical Almanac,* the value of S is given by:

$$S=0.0799''+0.272453 \, \pi$$

or the topocentric parallax is

$$\pi=\frac{S-0.0799''}{0.272453}.$$

In order to determine the maximum possible effect of the lunar augmentation arising from a favorable combination of circumstances, the extremely close perigee-syzygy situation of 1974 January 8.5 has been selected, having the following ephemeris values:

$$H_0=61' \, 30.0009''=1.025000250°$$
$$S_0=16' \, 45.43'' \quad =0.279286111°$$

Assuming that these large geocentric values had occurred simultaneously at a time in the lunar nodical cycle at which the Moon had reached its maximum declination of $\pm 28.5°$, and selecting also the geographic latitude $\phi=28.5°$ north or south, respectively, where the Moon would be seen in the zenith:

$$z'=0°; \cos z'=1; \sin z'=0$$

Since:

$$\sin H_0=0.017888675$$
$$\sin^2 H_0=0.000320005$$

[e] The exact equation for determining the topocentric parallax π from the equatorial horizontal parallax H_0, at any latitude ϕ, taking into account the flattening f of the Earth is:

$$\pi=H_0 \, (1-f \sin^2 \phi+5/8 \, f^2 \sin^2 2\phi+ \ . \ . \ .)$$

Therefore:

$$S=0.004996058+0.000089373+0.279286111$$
$$=0.284371542°=17' \, 3.7376''$$
$$=1023.7376''$$

$$\pi \text{ (topocentric)}=\frac{1{,}023.6577''}{0.272453}$$
$$=3{,}757.1900''=62' \, 37.1900''.$$

Thus, under these assumed conditions, with the Moon at one of its closest approaches to the Earth, at its greatest possible declination, and directly in the zenith of the place, the augmentation of the topocentric parallax over the geocentric parallax is 1′ 7.1891″. Although this increase is relatively small, the concept of lunar augmentation is included here in order to consider all possible factors which might have a contributing influence in the production of unusually high tides at the times of perigee-syzygy.

Since the influence of a closer lunar proximity resulting from the phenomenon of lunar augmentation is most strongly exerted when the Moon is in the zenith, the possible combination of this effect with the augmented gravitational forces responsible for perigean spring tides would occur: (1) at the Earth's Equator when the Moon is on the celestial equator; (2) along the Tropic of Cancer and the Tropic of Capricorn near the times of the vernal equinox and the autumnal equinox, respectively; (3) at geographic latitudes extending farther north and south, as the Sun (and with it the Moon) reach higher monthly declinations, culminating at the times of the summer and winter solstices, respectively, in the Northern and Southern Hemispheres; and (4) during those particular portions of the lunar nodical cycle (fig. 36) in which a ±5° increase in lunar declination occurs; the maximum augmentation effect on the tides would be felt at these same angular distances (±5°) farther north and south in latitude on the Earth's surface.

Regional and Latitudinal Effects on the Tides Resulting From Changing Lunar and Solar Declinations

Because of the numerically commensurable relations between the times of occurrence of the semimonthly excursions of the Moon from zero to maximum declination and the semiannual passage of the Sun through the same extremes, both temporal and regional variations in tidal action result from the combination of the lunar and solar declinational motions.

Where $\alpha_{☾}$ = the right ascension of the Moon
$\delta_{☾}$ = the declination of the Moon
☊ = the mean longitude of the ascending node of the lunar orbit

the relationship between lunar declination and lunar right ascension is given by the expression

$$\sin \delta_{☾} = 0.406 \sin \alpha_{☾} + 0.008 \sin 3\,\alpha_{☾} + 0.090 \sin (\alpha_{☾} - ☊) + 0.006 \sin (3\alpha_{☾} - ☊).$$

As far as the first and largest term on the right-hand side of this equation is concerned, it implies that the largest lunar declinations occur when the Moon has a right ascension equal to, or an odd multiple of 90° (i.e., if converted to hours of right ascension, at $\alpha = 6^h$, 18^h). Because the second term on the right contains an odd-number multiplier, 3, the same conditions contributing to the maximization of $\alpha_{☾}$ apply to this term as have been established for the first term.

The two previously specified values of right ascension, 6^h and 18^h, correspond to the positions where the Sun, in its apparent annual motion in the sky, passes through the summer and winter solstices (its positions of greatest northern and greatest southern declination, respectively). At the present astronomical epoch, the Sun reaches these positions within a day or two of the dates June 21 and December 22. From the first two terms in the above equation, the largest declinations of the Moon also should occur around these two dates. However, the effect of the Moon's celestial latitude β (perpendicular angular distance north or south of the ecliptic) has not yet been considered.

On these two dates, the new moon—if at conjunction in right ascension—will have the same α as the Sun. Since the solar declination at the times of either of the solstices has its maximum value, the lunar declination (always within 5°9′ of the Sun) also will be at a maximum if the Moon's celestial latitude is simultaneously at its greatest possible value.

All terms in the previous equations are sine functions. Hence, the greatest value of lunar declination resulting from the last two terms will occur when the differences between $(\alpha_{☾} - ☊)$ and $(3\alpha_{☾} - ☊)$ are also 90° or odd multiples thereof. But to give a value of 90° or an odd multiple of 90° in the third term of the equation, ☊ itself must always be separated by 90° or an odd multiple of 90° from the Moon. If the Moon is 90° distant from its ascending node, it is also geometrically at its greatest positive value of β, which conforms to the previous requirement. As before, the same relationship applies to the odd multiple of $\alpha_{☾}$ occurring in the fourth term of the equation.

Finally, at full moon, the right ascension of the Moon is always 180° or 12^h from the Sun. Therefore, to achieve a maximum lunar declination from the third and fourth terms, the position of ☊ must be 180° when $\alpha_{☾} = 270°$, and always 270° or an odd-integer multiple thereof from the Moon itself. If the Moon is 270° away from its ascending node, it is at its greatest negative value of β.

At either new moon or full moon, and with a right ascension which is equal to, or an odd multiple of 90°, the Moon will reach its normally largest declination for the year.

1. Solstitial Tides

An increase in the combined lunisolar diurnal forces by about 33 percent near the summer and winter solstices results in tides of greater diurnal inequality, amplitude, and range known as *solstitial tides*. Greater tidal amplitudes at the solstices also are added to by an increase in the Sun's component of motion in right ascension, an extension of the necessary catch-up time between the rotating Earth and the Sun, and a corresponding lengthening of the period of solar force application.

The Sun, in its apparent annual motion on the celestial sphere, moves from a declination of approximately −23.5° at the winter solstice to a declination near +23.5° at the summer solstice. The Moon's orbit, on the average, attains a maximum inclination to the ecliptic of only 5°9′.

The Moon must, therefore, in general quite closely follow the path of the Sun (although not necessarily the timing of the Sun itself) in its motions from maximum negative to maximum positive declinations and the reverse. Accordingly, each half-month, the Moon's position will change through declination values whose maximum range is from ±28.5° and whose minimum range is ±18.5°. The effect of the nodical cycle in increasing (or decreasing) the maximum lunar declination attained in any one year is described in part II, chapter 3.

2. Tropic Tides

In tropic regions, around latitudes 18.5°–28.5°, north or south, the maximum meridian altitudes of the Moon accompanying such maximum lunar declinations can reach 90° or nearly so, with the zenith distance of the Moon becoming 0° or a very small value. It will be shown (pt. II, ch. 5) that the tide-raising force of the Moon increases as the Moon reaches a position in the zenith. Hence, tides of greater amplitude and range, known as tropic tides, are produced in these low-latitude regions, and are felt as diurnal tides (table 19) even in high latitude regions of the Pacific Ocean.

3. Equinoctial Tides

The Moon crosses the ecliptic twice each month, once from north to south, and once from south to north, and is never more than 5°20′ from the ecliptic (its maximum possible inclination, due to perturbations).

The Sun, moving in the ecliptic, crosses the celestial equator twice each year at the vernal and autumnal equinoxes, about March 21 and September 23, respectively. When the Moon comes close to the true equinox positions, it must also lie very nearly in the plane of the celestial equator, at a time when the Sun is crossing this same great circle.

Thus, at times close to the equinoxes, the Sun and Moon are in almost the same declination plane (i.e., approximately 0°) as the Earth's Equator. The Sun's semidiurnal component of gravitational force will then add an extra 27 percent to the lunar force to provide a greater amplification of the Earth's tides. The tides resulting are known as *equinoctial tides*.

The effect of adding a close perigee-syzygy alignment to this already gravitationally reinforced tidal situation will be discussed in connection with *high* equinoctial spring tides in chapter 5, in describing those astronomical factors which lead to the maximization of perigean spring tides.

4. Latitudinal Effects of the Diurnal Inequality

The more common situation involving, for example, a differing height between higher high water and lower high water—and referred to as the *diurnal inequality*—is described in the appendix. Briefly, this phenomenon is created by a high declination of the Moon. The diurnal inequality also renders unequal the period of time between higher high water (HHW) and lower low water (LLW) compared with that between lower high water (LHW) and higher low water (HLW), and hence affects the duration of each. The effects of diurnal inequality usually increase with latitude and, to a greater degree, in the hemisphere to which the Moon's declinational motion carries it alternately during each half-month. However, the absence of any diurnal inequality when the Moon is over the Equator is general for all latitudes.

Subordinate Factors Influencing the Length of the Tidal Day

Certain definite relationships exist between the changing lengths of the apparent solar day and those of the lunar (and tidal) days which are a direct function of the positional changes of the Sun and Moon.

1. Solar Declinational Effects

When the Sun is on the celestial equator, the lengths of the day and night are very nearly equal at the Equator (although the length of the day increases slightly with geographic latitude). With the Sun at the summer solstice, the lengths of day and night remain approximately the same at the Equator, but the length of the day is as much as 6 hours longer at latitude +60°. The same situation applies in the Southern Hemisphere at the winter solstice. As the Sun moves away from the celestial equator, its maximum (meridian) altitude above the horizon also becomes greater. In consequence, since the Sun must move over a longer daylight path from horizon to horizon—although its apparent daily motion in right ascension is larger—the duration of daylight is extended.

2. Effects Due to Changing Parallax and the Obliquity of the Ecliptic

Because of the effects of the Earth's orbital eccentricity and inclination on its daily motion, the apparent solar day may be approximately 15 minutes longer or shorter than the mean solar day (this constantly changing difference is designated as the "equation of time"). The similarity between this "equation of time" (caused by the difference between the Sun's actual and mean motions) and a second tide-influential pattern existing between the motions of the true and mean moons will be described in part II, chapter 3.

3. Lunar Declinational Effects

The same influences specified in connection with the Sun in (1) above hold approximately true for the Moon's position with respect to the celestial equator, although not to such a close degree, since the effects of large parallax and other factors are of greater consequence in altering the apparent orbital motion of the Moon. As the declination of the Moon increases, the period between moonrise and moonset remains approximately the same at the Equator, but this interval increases very significantly at higher latitudes. The lunar (and tidal) days are lengthened in proportion.

4. Effect of the Moon's Orbital Inclination to the Horizon

Near the time of the autumnal equinox, with the full moon at the vernal equinox opposite the Sun, the Moon's orbit is inclined at a very small angle with respect to the horizon at middle and high latitudes in the Northern Hemisphere (particularly, if the Moon's ascending node also coincides with the vernal equinox). This circumstance results in the fact that the full moon rises above the horizon very slowly and with only a slight daily retardation for several successive nights. By rising at essentially the same time and hanging low in the sky for an extended period of time on consecutive evenings, it provides extra illumination for fall harvesting. Accordingly, this phenomenon has been given the name "harvest moon," and the full moon following a month later under nearly the same circumstances has been designated "hunter's moon."

From a tidal point of view, the slowly moving Moon possessing but a small daily lunar retardation implies an accompanying fast catch-up time between a point on the rotating Earth and the orbiting Moon. This results, in turn, in a relatively short tidal day, and a *reduced* period of application of any amplified tidal forces.

5. Supplementary Influences

In succeeding chapters, the extension of the lunar and tidal days will be seen to be of importance in providing extra periods of time within which augmented tide-raising forces such as those associated with perigee-syzygy can act. This influence applies in particular to those cases in which the Moon is near its maximum possible declinations. As will be noted in this same connection, the tidal flooding potential may, therefore, also be increased by the diurnal inequality.

The influence of a combined, two-dimensional alignment of the gravitational forces of the Moon and Sun in both right ascension and declination as the Moon crosses one of its two nodes coincidentally with the attainment of new moon or full moon, producing a solar or lunar eclipse, will be treated in chapter 5.

Seasonal Factors Influencing the Production of Heightened Tides

As a further extension of the previously outlined principles relating the positions and motions of the Moon to the amplitudes and durations of the tides, certain seasonal effects also are noteworthy.

In summer, the rotational axis of the Earth is tilted toward the Sun. It is, therefore, also inclined toward the position of new moon, which must lie along the line of syzygies and between the Earth and the Sun. This fact implies that, close to the time of the summer solstice, in the Northern Hemisphere, tides experienced during the day should be higher, and those observed during the night should be lower because of the relative gravitational force components involved. These effects are independent of any other hydrographic, oceanographic, or meteorological influences.

The inclination of the North Pole toward the Moon not only puts the Moon in the zenith at latitudes farther north, but renders the line of the Moon's gravitational force action shorter and more nearly perpendicular for Northern Hemisphere positions on the side of the Earth turned toward the Moon. The new moon, in line with the Sun, will cross any local meridian about noon, local apparent time, and, located centrally in the sky, will exercise its maximum influence in the Northern Hemisphere only during these midday hours.

During the full phase of the Moon, just the opposite of the above situation is true, with nighttime tides higher, and daytime tides lower, in the Northern Hemisphere. Since the Earth's axis is inclined away from the Sun (and toward the full moon on the opposite side of the Earth from the Sun) in winter, the same tide-raising force considerations indicated in the preceding paragraph hold but are now related to the full phase of the Moon. The full moon transits the local meridian about midnight, apparent time, and its maximum gravitational effects in the Northern Hemisphere are felt only during these late nighttime hours.

In spring and autumn, with the Earth's rotational axis inclined at right angles to the plane containing Earth and Moon, the tides produced at the two positions of lunar quadrature should be equally high as far as seasonal causes are concerned, but should occur in unequal periods of time. If the Moon is above the horizon at first-quarter phase, the floodtides should be smaller and of shorter duration than the ebbtides; if the Moon is below the horizon at this time, floodtides should be larger and last longer than ebbtides. At last-quarter phase, just the opposite is true. In spring, also, the conditions at the two quadratures are the exact reverse of those encountered in the fall. Again, all of the above influences are astronomical, and are not inclusive of local effects produced by other causes.

Effects of the Phase Inequality and Diurnal Inequality

The origin of the phenomenon of *phase inequality* lies in the synodic revolution of the Moon, which is responsible for the regular succession of lunar phases as seen from the Earth. This phenomenon is characterized by a variation of tidal forces associated with different geometric configurations and the resulting vector additions or subtractions of the gravitational forces of the Sun and Moon.

Such tidal force variations are caused by the alternating reinforcement of tidal forces created by the alignment of Sun, Earth, and Moon at the position of syzygy, and the opposition of these same forces at the times of lunar quadrature. A wide range of relative force values exists for all positions in between. The basic concepts of lunar phase production are fully explained in the appendix (fig. 3) and will not be repeated further here.

The *diurnal inequality* is caused by the position of the Moon (and/or Sun) over a latitude north or south of the Equator, and results in the two successive high waters and/or low waters being of unequal heights—or in a single low water. This phenomenon is also discussed in the appendix.

Certain perturbations of the lunar orbit resulting from the gravitational attraction of the Sun will be described in the next chapter. The special conditions resulting from the combination of perigee with syzygy which constitute the main topic of this work will be reserved for substantive discussion in part II, chapter 4.

The foregoing sections of part II, chapters 1 and 2, together with the appendix, provide a reasonably comprehensive summary of the principal astronomical influences affecting the tides. All of these effects must be considered as acting upon, causing potential modifications in, or adding their contributions to, the particular factors causing perigean spring tides. It must further be emphasized, strongly and repeatedly throughout this monograph, that the forces producing the tides are of harmonic nature and that none of these effects is totally independent of the other or may be so regarded.

Although the isolation of the astronomical elements associated with the production of perigean spring tides of various degrees of intensity and the satisfactory confirmation of the special case of proxigean spring tides are capable of direct analytic and empirical treatment, the establishment of the relative tidal flooding potential of such tides, when taken in conjunction with various meteorological factors, is not a simple, straightforward task. The following chapters represent an effort in this direction.

Chapter 3.

The Action of Various Perturbing Functions in Establishing, Altering, and Controlling the Amplitudes of Perigean Spring Tides

In chapters 1–2 of part II, certain standard astronomical principles and nomenclatural definitions have been introduced pro forma. These are valid without modification for all conditions in which the gravitational forces present are assumed to act in accordance with Newton's law of gravitation, upon unit or point masses, and in a closed two-body dynamic system, without the intervention of any disturbing functions exterior to the system. Such would be the case if the Moon were revolving in an unperturbed Keplerian ellipse.

However, the presence of the Sun in the system complicates matters to a considerable extent by exerting its own very major force influences. This action serves continuously to disturb the motions of both the Earth and the Moon in their respective orbits. The result is to produce so-called *perturbations* in the orbits of both bodies. In the case of the Moon, the existence of these perturbations—through their accompanying changes in (1) the lunar longitudes, (2) the instantaneous distances (or parallaxes) of the Moon, (3) various of the lunar orbital elements, and (4) the times of occurrence of the phase aspects or configurations, in turn exercises an important influence on the tides.

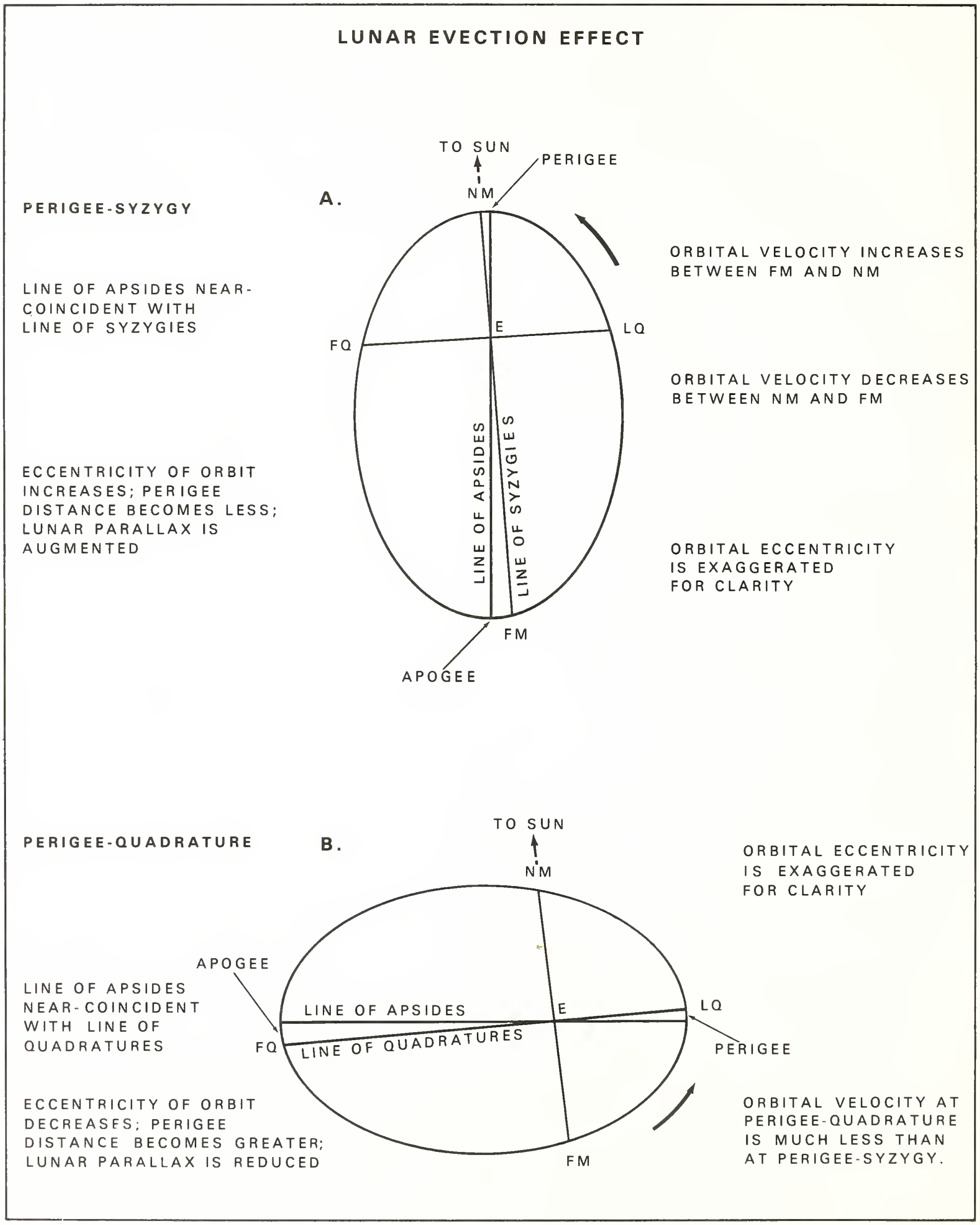
The Effects of Perturbations Upon Lunar Distances and Orbital Motions

Lunar perturbations consist of dynamic disturbances in the instantaneous positions and orbital motions of the Moon, resulting principally from the individual gravitational attractions of the Sun and Earth, as well as their mutual interactions. The dynamic conditions present belong ostensibly to the classic problem of three bodies in celestial mechanics. However, the comparative proximity of the Moon to the Earth, the unsymmetrical geodetic configuration and mass distribution of the terrestrial body, and the fact that the orbit of the Moon is in no sense a re-entrant one and permits only the establishment of an instantaneous osculating orbit, result in many nonperiodic variables which cannot be described by standard three-body methods. In lunar theory, the analytic solution of the Moon's orbit involves 36 differential equations, which cannot be treated rigorously.

Nonetheless, an empirical knowledge of the orbital motion of the Moon is well established by observations extending over many centuries, and most of the irregular motions of this body resulting from perturbative influences are well known. Only those perturbations which relate to, and have a perceptible effect on, the Earth's ocean tides will be discussed in this work. The astronomical origins of these perturbations as they affect the instantaneous longitude and the differential motion of the Moon in this coordinate, as well as the eccentricity, major axis, and instantaneous shape of the Moon's orbit, the geocentric horizontal parallax, the variable motion of perigee, and the length of the lunar day all will be described in the present chapter. The corresponding influences of these astronomical variations upon tidal parameters will be reserved for chapters 5–6.

The Lunar Evection

The first and foremost, largest, and earliest discovered influence among the lunar perturbations is the *lunar evection*. This is a perturbation producing a continuous alteration in the shape of the Moon's orbit, and is a function of


LUNAR EVECTION EFFECT
A.
TO SUN
NM
PERIGEE
PERIGEE-SYZYGY
LINE OF APSIDES NEAR-COINCIDENT WITH LINE OF SYZYGIES
ORBITAL VELOCITY INCREASES BETWEEN FM AND NM
E
FQ
LQ
ORBITAL VELOCITY DECREASES BETWEEN NM AND FM
LINE OF APSIDES
LINE OF SYZYGIES
ECCENTRICITY OF ORBIT INCREASES; PERIGEE DISTANCE BECOMES LESS; LUNAR PARALLAX IS AUGMENTED
ORBITAL ECCENTRICITY IS EXAGGERATED FOR CLARITY
FM
APOGEE
PERIGEE-QUADRATURE
B.
TO SUN
NM
ORBITAL ECCENTRICITY IS EXAGGERATED FOR CLARITY
APOGEE
LINE OF APSIDES NEAR-COINCIDENT WITH LINE OF QUADRATURES
LINE OF APSIDES
E
LQ
FQ
LINE OF QUADRATURES
PERIGEE
ECCENTRICITY OF ORBIT DECREASES; PERIGEE DISTANCE BECOMES GREATER; LUNAR PARALLAX IS REDUCED
FM
ORBITAL VELOCITY AT PERIGEE-QUADRATURE IS MUCH LESS THAN AT PERIGEE-SYZYGY.

the relative positions of the line of syzygies with respect to the line of apsides in the lunar orbit (see figs. 26A, B).

The effects of this disturbance upon the Moon's orbital motion are twofold: When the line of apsides and line of syzygies coincide, the Moon moves faster in celestial longitude *between* the phases of full moon and new moon and slower between new moon and full moon. In addition, when these same two axes come together, the eccentricity of the lunar orbit is increased, producing a redistribution of the Moon's velocity in orbit.

Figures 26A, B.—Lunar evection consists of a periodic fluctuation in the eccentricity of the lunar orbit as a function of the phase angle and true anomaly of the Moon (its instantaneous angular differences in longitude from the positions of conjunction and perigee, respectively). This phenomenon results in changes in the eccentricity of the lunar orbit, produced by the combined interaction of the tangential and normal components of the Sun's gravitational force.

To illustrate the effects of evection throughout a complete lunar revolution, a condition of perigee-syzygy alignment will initially be assumed. At perigee-syzygy, the tangential component of the solar gravitational force, here applied at right angles to the lunar orbit, is ineffective in altering the eccentricity of the orbit; however, the normal component of the Sun's force is negatively effective and tends to increase the orbital eccentricity.

As the Moon moves from the position of perigee-syzygy, the normal component decreases, while the now-negative tangential component acts to decrease the eccentricity. The superposition of these two forces results in an eventual balance and a condition of zero change in eccentricity somewhere between perigee-syzygy and a point approximately 54°44′ along the orbit. Thereafter, the eccentricity decreases until the Moon reaches a position following apogee-syzygy.

As the Moon passes through the vicinity of apogee-syzygy (a position never as well defined as perigee-syzygy), the same process occurs in reverse as the eccentricity—after a brief interval similar to the preceding during which a balance is reached between the tangential and normal components of force—now steadily increases while the Moon approaches perigee-syzygy.

The net result is that, following upon any given alignment of perigee-syzygy, the effect of evection decreases the eccentricity of the lunar orbit during slightly more than half of a synodical revolution. The eccentricity of the orbit then increases during the succeeding half-revolution, plus a little more.

The associated variable gravitational force factors are of greatest consequence in their contribution to tide-raising action in the period just prior to perigee-syzygy, when the influence of evection has collectively resulted in: a maximum increment in orbital eccentricity; the greatest reduction in perigee distance of the Moon; a significant augmentation in the lunar parallax; and a corresponding increase in orbital velocity to add to the Keplerian increase in velocity at times of perigee (see the necessary velocity catch-up effects discussed in chapter 6).

However, *exactly* at the configuration of perigee-syzygy, the acceleration in lunar velocity due to this perturbation is zero and, close to the position of perigee-syzygy, it is nearly so. As a result of the previously mentioned increase in the eccentricity of the lunar orbit at perigee-syzygy, the main contribution of the lunar evection to the phenomenon of perigean spring tides therefore comes about through an accompanying marked increase in the geocentric horizontal parallax of the Moon. This reduction in the lunar distance at perigee-syzygy, with its corresponding increase in gravitational tide-raising forces, will be treated extensively in a later section of this chapter. The influence of this perturbative function will also be discussed later in connection with the differences between mean and true lunar parallax and mean and true lunar longitude.

Finally, if a coincidence occurs between the line of apsides and the line of quadratures, the eccentricity of the lunar orbit decreases, and the Moon moves slower at this time. But this circumstance bears no direct relationship to the occurrence of perigee-syzygy responsible for perigean spring tides.

The Lunar Variation

The second important perturbative influence is the *lunar variation*. Lunar variation is a function completely dependent upon the particular longitudinal orientation of the Sun with respect to the orbit of the Moon. This phenomenon is responsible for a continuously changing shape of the lunar orbit. The change in orbital figure takes place through a lengthening of the orbit along an axis at right angles to a force vector extended from the Sun toward the lunar orbit.

In its causal relationship, the Moon's variational effect is entirely independent of the angle between the line of apsides and the line of syzygies. However, as the result of the variation, the respective sections of the Moon's orbit on the same and opposite sides of the Earth from the Sun become less sharply curved. The corresponding lunar distances from the Earth are reduced in these two sections by the Sun's perturbational influence.

Significantly for the present discussion, if the Moon happens to be simultaneously along this force-axis connecting Sun and Earth (i.e., the line of syzygies), its distance from the Earth is slightly reduced, and its horizontal parallax is increased. This effect supplements the variable distances imposed by the revolution of the Moon in an elliptical orbit (the elliptical variation) and resulting from the opposite orientations of perigee and apogee. However, if the line of apsides and line of syzygies coincide, the

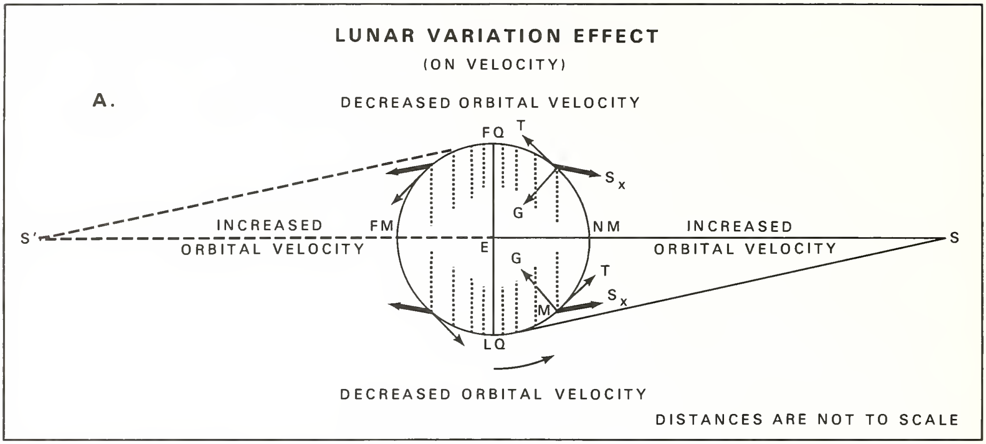


FIGURE 27A.—The phenomenon of *lunar variation* results from the considerable range of distances of the Earth and Moon from the Sun (and the corresponding difference between the Sun's gravitational force upon these two bodies) at various lunar phases. At the quadratures, the solar gravitational force acting upon the Moon and the Earth is the same; at the syzygies, the greatest difference in solar gravitational force upon these two bodies exists.

On the side of the Earth nearest the Sun, the Sun attracts the Moon away from the Earth with constantly increasing force as the distance of the Moon from the Sun diminishes between LQ and NM. This force is exerted with its predominant component S_x contributing a significant accelerative action parellel to one of the two rectangular components of velocity subject to which the Moon is moving. (The gravitational or centripetal component is directed along MG; the tangential or centrifugal component is exerted along MT.) A velocity accelerating influence is applied cumulatively (the angle of effective force action, $<$ MSE, decreasing while the magnitude of the force itself increases) between LQ and NM.

Since, between NM and FQ, the solar force is exerted with its principal component opposite to the corresponding velocity component of the Moon's tangential motion, a negative acceleration (deceleration) results. Thus the Moon's velocity is accelerated between LQ and NM and retarded between NM and FQ.

On the opposite side of the Earth from the Sun, between FQ and LQ, the Moon is more distant from the Sun than the Earth is, and the latter body is pulled away from the Moon. The difference in the relative forces of the Sun on the Moon and the Earth increases steadily as the Moon approaches FM. In the gravitational action, the effect is exactly the same as would occur if an imaginary Sun were located at S′, at the same distance as S from E, alon g the line of syzygies extended.

For the same reasons above enumerated, between FQ and FM, the Moon's motion is accelerated, with a maximum velocity attained at FM. Between FM and LQ, the Moon's motion is retarded, to a minimum at LQ.

The lunar orbital velocity resulting from the effect of lunar variation is, therefore, greatest at the syzygies and least at the quadratures. As seen in figure 27B, correspondingly varying centrifugal forces result in a varying configuration of the lunar orbit.

lunar evection can measurably increase the value of the parallax and reduce the lunar distance at the time of perigee-syzygy. The increased tidal forces produced by the diminished distance of the Moon are related to a composite of changes in several orbital parameters, as described below.

1. Alternating Acceleration and Deceleration of the Moon's Orbital Motion

The first factor contributing to ultimate variations in the tide-raising forces involves the changing angle between the direction of the Sun from any given point in the Moon's orbit and a tangent line from this same point. The tangent line also represents the instantaneous vectorial direction of the Moon's motion in its orbit. At third-quarter phase (fig. 27A) (except for the small angle subtended by the radius of the lunar orbit at the distance of the Sun) the tangent line from the Moon's orbit is oriented almost directly toward the Sun and the Sun's gravitational force is fully effective in accelerating the orbital velocity of the Moon. As the Moon moves toward conjunction, the angle between the force vector from the Sun to the Moon and the Moon's velocity vector increases from 0° to 90°. At new moon, the Sun's gravitational force vector is directed exactly at right angles to the Moon's orbital motion and exerts a zero influence in producing any change in orbital velocity.

Between new moon and first quarter, and again between full moon and third quarter, the situation is just reversed, as the angle between the Sun and the Moon's velocity vector decreases from 90° to 0°, and the orbital deceleration of the Moon varies from zero to a maximum. Likewise, the changing angular relationship that exists between third quarter and new moon prevails between first quarter and full moon, but with the Moon's velocity vector now oriented in the opposite direction in the sky. Between first quarter and full moon, the angle separating the two vectors increases from 0° to 90°.

In recapitulation of the forces acting, at new moon and at full moon, since the gravitational attraction of the Sun acts at right angles to the Moon's orbital motion, no increase in acceleration is produced. However, in moving away from these two positions, the orbital acceleration of the Moon is altered by the Sun's gravitational force and attains maximum positive and negative values when the full force of the Sun is exerted directly along tangent lines to the lunar orbit at the positions of third quarter and first quarter, respectively.

2. Changing Lunar Orbital Velocity With Respect to the Earth

A second important influence of the lunar variation results from the combination of the previously described effects and the fact that the Moon moves from a position inside the Earth's orbit around the Sun to a position outside this orbit during each monthly revolution. If only the effect of the Sun's gravitational influence on the Moon during these revolutions were considered, the resulting lunar motion would be a relatively simple one. Consider, for example, the single effect of the Sun's gravitational influence as the Moon moves from its position of conjunction (between the Earth and the Sun) and revolves toward its position of opposition, 180° from conjunction, on the side of the Earth farthest from the Sun. In this outgoing portion of the Moon's motion with respect to the Sun, it would be moving against the Sun's gravitational attraction (and its motion would, accordingly, be subject to a retardation). Conversely, on the return portion of its orbit, from opposition to conjunction, the Moon might be thought of as "falling" toward the Sun (and hence accelerating in its velocity of motion).

Such a simplified assumption is not the true case, since the gravitational force of the Sun is also exerted on the planet Earth. This results in the condition actually present, in which a clear-cut distinction between the forces acting must be observed:

When the Earth, Moon, and Sun are aligned at either new moon or full moon, the gravitational attractions of the Sun and Moon tend to reinforce each other in their actions on the Earth's tides. However, in considering the reciprocal forces exerted on the Moon, the gravitational force of the Earth is respectively reduced or increased by that of the Sun at the positions of new moon and full moon. The reasons for the latter circumstance will now be described.

In moving from the position of new moon to a position very nearly that of first quarter, the Moon is at all times closer to the Sun than the Earth is, and hence is at all times being attracted more by the Sun, and in a direction slowing the Moon's orbital motion. As the Moon revolves from a path normal to the line connecting it and the Sun at new moon to a path nearly along this line at first-quarter position, the attraction of the Sun upon the Moon is exerted in a direction increasingly more opposed to the Moon's orbital motion. In addition, as the Moon nears first-quarter phase, a small sideward component of lunar deflection increases, directed toward the Earth, but caused by the Sun. This latter circumstance results from the fact that the Moon makes a small acute angle (as seen from the Sun) with the line connecting the Sun and Earth. The Sun's gravitational attraction exerted along this line possesses a slight component impelling the Moon inward toward the Earth. Both this inward deflection and the fact that the gravitational attraction of the Sun on the Moon is exerted in a direction increasingly more opposed to the Moon's orbital motion (thereby effectively reducing the latter) create the net result of diminishing the Moons orbital velocity with respect to the Earth.

In revolving through the first-quarter phase and passing on toward the far side of the Earth and the position of full moon, the Moon moves to a greater distance from the Sun than the Earth has. The attraction of the Sun for the Earth—both because of the Earth's larger mass compared with that of the Moon and the Earth's closer distance to the Sun—becomes greater than the Sun's attraction for the Moon.

Because a relative separation occurs between the Moon and the Earth, the effect of gravitational (centripetal) force in restraining the Moon to the Earth is reduced, and the satellite's own centrifugal force (associated with revolution in orbit and tending to cause an outward deflection of the Moon) is augmented. The radius of curvature of the Moon's orbit is increased, and along this straighter portion of the orbit, the motion of the Moon with respect to the Earth is speeded up. The relative motion between the Moon and Earth is continuously accelerated until the position of full moon is reached and the Moon's orbital motion is precisely at right angles to the gravitational force vectors of the Earth and Sun.

Conversely, between full moon and third quarter, the Earth is subject to the Sun's gravitational attraction acting in the same direction as that of the Moon's motion. Because the Earth is closer to the Sun than the Moon is during this period, the Moon's velocity with respect to the Earth is effectively reduced. But as the Moon passes third-quarter phase, its distance from the Sun again becomes less than that of the Earth's distance from the Sun. Responding to the consequent increase in gravitational force, the Moon's motion with respect to the Earth is accelerated as it moves toward the position of new moon. At new moon, this acceleration ceases, since the Moon's motion is here again completely at right angles to a line joining Moon and Sun.

In summary, at the syzygies, the Sun decreases the gravitational attraction between the Earth and Moon by separating the one which is closest to it from the other. At the quadratures, the full gravitational force of the Earth on the Moon is effective, undiminished by that of the Sun, which in these cases is exerted at right angles to the force vector joining the Earth and Moon. The explanation of why the Moon, in consequence, travels faster in its orbit at the syzygies and slower at the quadratures is contained in the next section.

3. Changes in Curvature of the Lunar Orbit

A subsidiary effect of the lunar variation is a flattening of the orbital curvature (i.e., an increase in the radius of curvature) at the lunar syzygies, coupled with the creation of a more sharply curved orbit (smaller radius of curvature) at the times of the lunar quadratures. Immediately, however, it must be emphasized that these dynamic effects are small, are superimposed upon, and act as modifiers of, the larger and more meaningfully fluctuating orbital parameters of eccentricity, semimajor axis, and mean parallax. The lunar variation involves a small individual difference between the lunar distances from Earth at the times of the syzygies and the quadratures, but only a secondary influence upon the lunar distances at perigee-syzygy.

In this connection, the concept of a smaller radius of curvature in terms of a more sharply curved orbit but a slower orbital motion of the Moon should not be confused with (1) a greater orbital eccentricity, which indicates only a more elongated orbit, with the most sharply curved portions at the two apsides, or (2) a larger geocentric parallax which, because of the inverse relationship in its definition, implies a closer distance of the Moon to the Earth, with the closest proximity thereto occurring at the time of extreme perigee-syzygy.

At the position of perigee, which lies along the major axis as well as along the line of apsides of the lunar orbit (the former is but a portion of the latter), the curvature of the orbit, all factors considered, remains at maximum (i.e., the radius of curvature is the least).

In accordance with dynamic principles, the centrifugal force of the Moon at any point in its orbit varies directly as the square of its velocity of revolution. It is this outwardly directed force which must be just balanced by the inwardly directed gravitational force of the Earth at any point in order for the Moon to remain in a stable orbit. Since the centripetal or gravitational force of the Earth upon the Moon does not vary except with the Moon's changing distance from the Earth, any change in orbital velocity and in the resulting centrifugal force must be balanced by a corresponding change in the Moon's distance from the Earth.

As the Moon changes its distance from the Earth, the radius vector between the Moon and the Earth likewise changes in length. This radius vector also corresponds with the radius of curvature at any point in the Moon's orbit. Therefore, according to the above relationships, when the Moon slows down, the Earth-Moon distance becomes less and the curvature of the orbit becomes more pronounced. Whenever the Moon accelerates and the radius of curvature and corresponding circumference of the orbit become larger, the orbital curvature is reduced and the orbit itself becomes more nearly a straight line. A comparison will now be made between the actual conditions existing in the disturbed (three-body) lunar orbit compared with those that would theoretically exist if only the gravitational effects of the Earth on the Moon (two-body problem) were considered.

At points 45°, 135°, 225°, and 315° around the orbit from the position of new moon (dividing the orbit into octants), the curvature of the disturbed orbit corresponds exactly with that of the undisturbed orbit. At these points, which separate the regions of least and greatest orbital curvatures, the curvature is the same as that in the two-body orbit.

Combining these relationships with the previously derived conditions of acceleration and retardation of the Moon's motion at various points in its orbit, the following summary of conditions is obtained: between 315° and 45°, and between 135° and 225°, the orbital curvature is the least; between 45° and 135°, and between 225° and 315°, the orbital curvature is the greatest.

Since the actual eccentricity of the lunar orbit is quite small (0.054900489), its undisturbed configuration may, for purpose of graphic representation, be regarded as a circle. The perturbed orbit resulting from the effect of lunar variation alone may then be comparatively represented by the elliptical orbit shown in figure 27B.

The Elliptic Variation

The elliptic variation is, in actuality, not a true physical perturbation, but a variation of periodic nature in the Moon's motion which occurs as a result of the Moon's monthly revolution around the Earth in an elliptical orbit. As described in part II, chapter 2, this motion results in the Moon's alternating passage through the perigee and apogee positions in its orbit where it is respectively at its closest and farthest distances from the Earth in each monthly cycle.

As in all of the other examples of physical perturbations, this effect is accompanied by a corresponding increase in, and reduction of, the gravitational force exerted by the Moon upon the tidal waters of the Earth. The amount of the distance variation, in the present case, can be represented completely by means of a simple quantitative function, viz., the geocentric horizontal parallax of the Moon. The actual increase in the value of this term at the times of perigee-syzygy—and the augmented gravitational force resulting—will be discussed in several ensuing sections.

The minimum parallax of the Moon is 3,235″, corresponding to a maximum possible distance from the Earth of approximately 406,154 km or 252,364 mi; the maximum lunar parallax is 3,692″ which corresponds to a minimum Earth-Moon distance of about 355,880 km or 221,126 mi (fig. 41). From a tidal standpoint, the elliptic variation is equivalent to the lunar inequality.

The Annual Variation

This perturbation in the Moon's apparent position results from the Earth's annual revolution around the Sun in an elliptical orbit, carrying the Moon with it. The origin of the analogous tide-related phenomenon of solar parallactic inequality has been discussed in part II, chapter 1. Its effect is that of bringing the Earth, revolving in an elliptical orbit, to a position of closest annual approach to the Sun (perihelion) around January 2–4 of each year, and causing the Earth to withdraw to its greatest distance from the Sun about July 3–6. Tied to the Earth by mutual gravitation, the Moon shares this same motion.

The satellite body revolves around the Earth in an elliptical orbit which, subject to maximum perturbations, can cause an overall variation of about 50,274 km (31,238 mi) in distance from the Earth. At the same time, the Moon, along with the Earth, undergoes a larger variation in distance from the Sun caused by the Earth's annual motion in an elliptical orbit. The Sun-Earth distance can vary from about 147,100,000 km (91,408,000 mi) to 152,100,000 km (94,515,000 mi). The Sun-Moon distance will fluctuate over a still greater range, depending on which side of the Earth the Moon is at the time considered.

The maximum effect of this variation in terms of reinforcing the already augmented gravitational and tidal forces associated with perigean spring tides will be evident around the time of solar perigee—the time of closest annual approach of the Moon to the Sun—which must occur within one-half of a lunar month of perihelion. The particular consequence of the annual variation is discussed later in this same chapter.

The Lunar Reduction

One further orbit-refining procedure it is necessary to consider astronomically in the representation of the Moon's precise position is applicable as a positional transformation known as the *lunar reduction*. The necessary corrective factor results from the difference between the Moon's true longitude in orbit and its apparent longitude in the ecliptic as conventionally tabulated. However, any effect upon tide-raising forces resulting from this corrective term is so small as to be considered negligible in the present discussion.

Differences Between the Mean and True Astronomical Positions of the Moon and Sun

As a matter of ready verification (tables 10, 17, 20), because of the Moon's elliptical orbit and the respective perigee and apogee effects upon the orbital velocity as predicted by Kepler's Law, the lunar velocity varies considerably throughout both the synodic and anomalistic months. The Moon slows down appreciably between perigee and apogee, and speeds up in nearly the same proportion between apogee and perigee.

For convenience in the prediction of tides, during an early period in which hand-computations were necessary, any permissible means of reducing the computational load

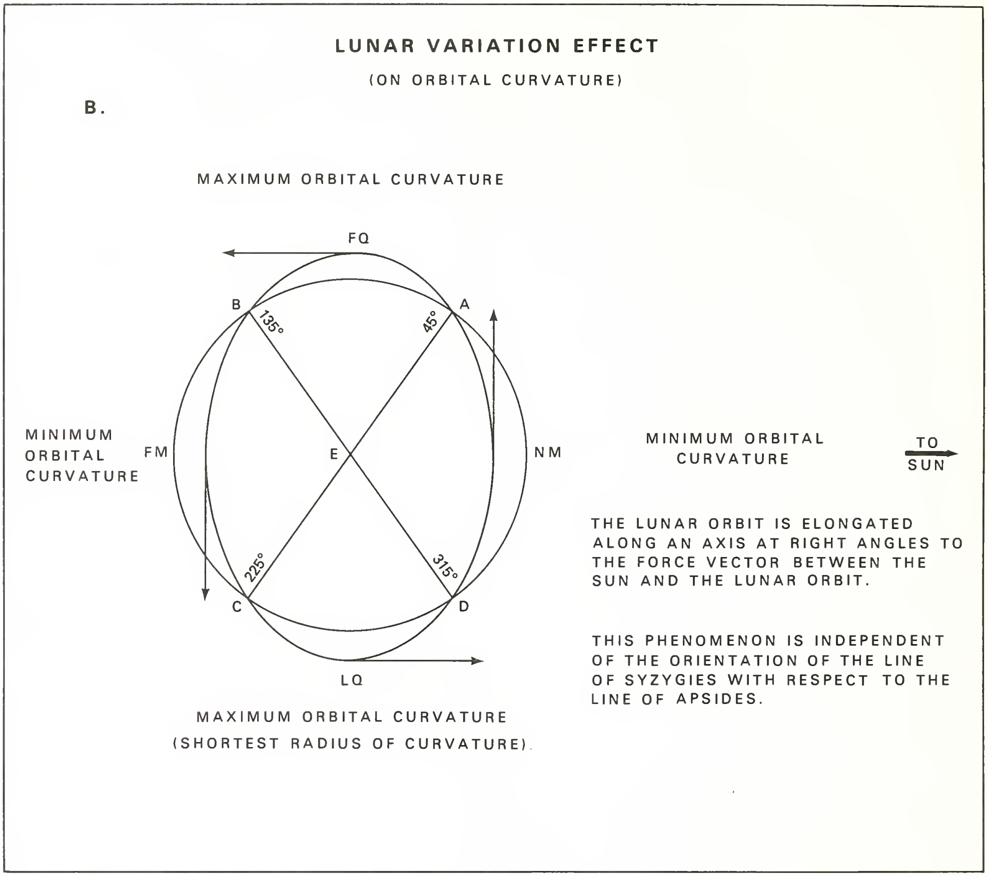


FIGURE 27B.—The phenomenon of lunar variation also results in changes in the shape of the lunar orbit. To demonstrate these changes more clearly, the Moon may initially be assumed to move in the circular orbit ABCD rather than in its true elliptical orbit of small eccentricity. As was seen in figure 27A, at FM, the Earth, being closer to the Sun than is the Moon, is pulled away from the Moon. The Earth's gravitational attraction on the Moon is thus decreased, and the centrifugal force generated by the Moon's revolution in orbit exceeds the centripetal force. The radius of curvature increases, the local curvature decreases, and this portion of the orbit becomes flattened.

At NM, the Moon similarly is pulled from the Earth. Here also the Earth's gravitational attraction for the Moon is decreased, the centrifugal force exceeds the centripetal force, and the Moon's orbit is flattened. The greater is the orbital velocity of the Moon, the more the centrifugal force exceeds the centripetal, and the greater is the orbit-straightening action.

As shown in figure 27A, the greatest velocity increase produced by the effect of lunar variation is at the syzygies and the greatest decrease is at the quadratures. Accordingly, the lunar orbit will be flattened to the greatest extent at the syzygies and possess the greatest curvature at the quadratures. Approximately midway between these four positions, the orbital path must pass through points of inflection where the curvature remains unchanged. In the octants (at angles of 45°, 135°, 225°, and 315° from NM), no alteration in the shape of the lunar orbit occurs from the effect of lunar variation. The unperturbed (circular) and perturbed (elliptical) orbits here coincide.

In the case of the Moon's actual elliptical orbit, the same extension of this ellipse along an axis perpendicular to the instaneous direction of the Sun takes place—together with a slight flattening in the orbital curvature close to the two positions where a line from the Sun cuts the orbit. The orbit-distorting effects of lunar variation are simply superimposed upon the true elliptical configuration, adding to the total complexity in the shape of the perturbed orbit.

resulting from the very numerous astronomical terms was highly desirable. The necessary and sufficient calculating procedure, involving minimum complexity, and capable of representing the lunar orbital velocity as well as other related functions, was sought after and instituted. Average values were freely resorted to wherever possible, and are still tacitly utilized in tidal computations.

Using basic formulae derived by Simon Newcomb in the late 19th century, the mean longitudes of the Moon and Sun, and various of their orbital parameters, were originally adopted for epochs corresponding to the first day of each year, and these values still appear in standard tidal reductions. In addition, mean values are employed for the daily angular motions (real and fictitious, respectively) of the Moon and Sun. The instantaneous mean positions of these two bodies are computed for any date subsequent to a standard epoch by adding their average (mean) daily motions to their positions at the time of the standard epoch.

The Derivation of True and Mean Astronomical Positions

The actual, observed position of the Moon or Sun at any time, reduced through the application of a correction for parallax to the Earth's center—and with other corrections for atmospheric refraction and diurnal aberration duly applied—becomes the true (apparent) astronomical position of the object.

It is important to observe at this point that the distinctions between *observed* and *apparent* positions for the Moon and Sun are the same as those applied generally to the positions of all celestial objects. However, the meanings of *true* and *mean* positions as used in the present connection are *not* the same as those of the terms *true place* and *mean place* used astronomically in relation to star positions.

For all celestial objects, the *observed* place is that determined by direct instrumental means by an observer on the surface of the Earth (topocenter), corrected only for errors in the instrument and others dependent on the method of observation (instrument collimation, leveling errors, inequality of the pivots and V's, index or circle errors, apparent semidiameter of the Moon or Sun, dip of the horizon, clock errors, etc.).

The *apparent* place is a geocentrically referred position (i.e., corrected by application of the geocentric horizontal parallax where necessary). It also includes reductions for astronomical refraction and diurnal aberration. Thus, in apparent place, the observed position is not only referred to the center of the Earth, but is free of atmospheric effects and the light-velocity altering influence of the Earth's diurnal rotation. The coordinate system in which the celestial object is referenced still includes the coordinate-altering effects of astronomical precession and nutation. Here any further resemblance ends between the position-referencing system for the Moon and Sun presently under discussion and an apparently similarly designated system for indicating the positions of the stars and other distant celestial objects.

By contrast, when the precise positions of the stars are considered, the origin of coordinates is the center-of-mass of the solar system (barycenter) which is very close to the center of the Sun (heliocenter). Because the distance of the Earth from the Sun and the velocity of the Earth's revolution around the Sun are now additionally involved, corrections for annual parallax and annual aberration, respectively, must be applied to the apparent place to yield stellar *true place*. As in the case of apparent place, true place is still given in a coordinate system which contains the effects of, and is uncorrected for, precession and nutation. The star position is referred to the true equator and equinox of the date of observation.

Finally, if a reduction for nutation is applied to stellar true place, the position of the star is represented in *mean place*. In all other respects except that the stellar position is now referred to the mean equator and equinox of the date of observation, *mean place* is exactly similar to *true place*. Mean place also still contains the uncorrected effects of precession.

The Assumption of Mean Positions

However, for tidal prediction purposes, the average or *mean position* of the Moon or Sun, referenced to a convenient zero-point in time by application of similarly averaged increments of mean daily motion, is used. The concept of mean position as used in tidal computations has been extended to include the mean longitudes of the Moon, the Sun, the position of lunar perigee, the position of solar perigee, the point of intersection between the celestial equator and the Moon's orbit (reckoned in the orbit plane), as well as the lunar ascending node. The mean positions and motions are referred to the origin of coordinates at an appropriate mean epoch, in each case.

The mean positions of these lunar and solar elements together with their mean daily motions appropriate to the years A.D. 1800–2000 are available in table 4 of *Manual of Harmonic Analysis and Prediction of Tides*[1] (1940). Certain values among the total list also are contained in tables of the Mean Orbital Elements of the Moon and the Inner Planets in annual volumes of *The American Ephemeris and Nautical Almanac*.

The value of the mean motion of the Moon in its own orbital plane is obtained from the relationship

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$$n_{☾}=\frac{360°}{M_{sid}}=\frac{360°}{27.321661^d}$$
$$=13.176396°/^d$$

The mean apparent motion of the Sun is similarly obtained from the mean angular velocity of the Earth in its orbit during a sidereal year

$$n_{\odot}=\frac{360°}{Y_{sid}}=\frac{360°}{365.256360^d}$$
$$=0.985647°/^d$$

However, because of the elliptical orbits of both the Moon and Earth, the two values determined above in no way express the real (lunar) or apparent (solar) angular velocities of these two bodies on any one day during an entire revolution. The real daily orbital motion of the Moon at perigee will be appreciably larger than the mean value, and the apparent daily motion of the Sun will be measurably faster at perihelion than the respective mean motion.

As a secondary step in these computations, the mean value of the lunar longitude, obtained as indicated above, is converted to an approximate true value by the application of arbitrary reduction coefficients representative of the lunar perturbations previously discussed. In addition, the value of the *true parallax* of the Moon expressed as a function of the mean parallax for each specified date enters into the tidal computations. Higher powers in these reduction equations are neglected, and various other simplifying assumptions are made, under the rationalization that the difference between the true and mean longitude of the Moon never exceeds 7.8° (0.137 radian) and that this latter value differs very little from the sine function (0.136) by which it is subsequently replaced.

The justification for this procedure in evaluating the true position of the Moon from its mean position may easily be supported, based on the fact that, for tidal computations of the order of accuracy heretofore required, the existing methods are adequate. The differences between the true and mean positions of the Moon are indeed quite small. For all ordinary predictions not subject to the computational refinements made necessary by increased knowledge of perigean spring tides, potential tidal flooding attendant thereon, and burgeoning coastal populations now vastly more dependent upon these predictions, the approximation would suffice. Furthermore, the maximum differences between mean and true positions in some significant cases (but, as will shortly be seen, not *all*) occur at times when the tide-raising forces are at their lowest possible values and, therefore, are not seriously affected by these differences.

Conversely, at the times of perigee-syzygy, when the tide-raising forces are considerably augmented, that part of the lunar evection term which acts to produce an accelerated motion in longitude, and a corresponding difference between true and mean longitude, completely disappears. However, in subsequent sections, it will be noted that other and equally important tide-producing factors, whose magnitude could vary sensibly with the difference between true and mean place, also occur at perigee-syzygy and are not self-compensating.

Further comment on the previously accepted simplifications and assumptions will, therefore, be reserved until certain lunar perturbations and resulting influences peculiar to the phenomenon of perigee-syzygy—and the production of perigean spring tides—have been discussed.

The Special Perturbative Influences of Lunar Evection and Lunar Variation

Hugh Godfray in *An Elementary Treatise on the Lunar Theory*[2] (1871) has provided an excellent exposition from which it is possible to derive the effects of the most significant individual perturbations. These establish the differences between true and mean position in the lunar orbit.

The effects of these perturbational terms are regarded as corrections to the mean longitude necessary to obtain the true longitude in orbit. By transforming the symbols in Godfray's equations to a compromise of those more familiarly used in *The American Ephemeris and Nautical Almanac* and other modern sources, the individual analysis of the several terms can proceed as below:

Where:

$\lambda_{☾}$ = the *true* longitude of the Moon

$n_{☾}$ = the *mean* daily angular motion of the Moon

$L' = n_{☾}t =$ the *mean* longitude of the Moon at any time t

L'_0 = the *mean* longitude of the Moon at $t=0$

$e_{☾}$ = the eccentricity of the lunar orbit

Γ'_0 = the *mean* longitude of the lunar perigee at time $t=0$

$\Gamma' = (1-c)\, n_{☾}t + \Gamma'_0 =$ the *mean* longitude of the lunar perigee at any time t, assuming a uniform rate of motion

c = an arbitrary factor introduced by Clairaut to indicate that the lunar perigee is itself in motion

b = a factor similar in purpose and usage to that of c

N = the position of the lunar node when the lunar longitude is $\lambda_{☾}$

$s = \tan N$

Ω=the longitude of the *mean* ascending node of the lunar orbit on the ecliptic

$\lambda_{\odot}$=the *true* longitude of the Sun

$n_{\odot}$=the *mean* apparent daily angular motion of the Sun

$p=\frac{n_{\odot}}{n_{☾}}$= the ratio of the *mean* daily angular velocity of the Sun to that of the Moon (=0.0748)

L_0=the *mean* longitude of the Sun at time $t=0$

$L=n_{\odot}t+L_0=n_{☾}pt+L_0$= the *mean* longitude of the Sun at any time t

$e_{\oplus}$=the eccentricity of the Earth's orbit

Γ_0=the *mean* longitude of the solar perigee at time $t=0$

Γ=the *mean* longitude of the solar perigee at any time t.

The general equation which includes all of the principal perturbational terms is:

$\lambda_{☾}$ (true longitude of the Moon)

$=L'$ (mean longitude of the Moon)

$+2e_{☾}\sin(cL'-\Gamma'_0)+\frac{5}{4}e_{☾}^2\sin 2(cL'-\Gamma'_0)$

(elliptic inequality)

$+\frac{15}{4}pe_{☾}\sin[(2-2p-c)L'-2L_0+\Gamma'_0]$

(evection)

$+\frac{11}{8}p^2\sin[(2-2p)L'-2L_0]$

(variation)

$-3pe_{\odot}\sin(L-\Gamma_0)$

(annual equation)

$-\frac{1}{4}s^2\sin 2(bL'-\Omega)$

(reduction)

In keeping with the purpose of this investigation, a detailed analysis will be made only of those actual perturbational functions which are capable of producing a meaningful change in some tide-related parameter at a time of perigee-syzygy. Somewhat simplifying the second additive term in the previous equation, the correction for *lunar evection* may be written as

$$\lambda_{☾}=L'+\frac{15}{4}pe_{☾}\sin[2(L'-L)-(L'-\Gamma')]$$

Because, at the syzygies, $L=L'$, and since $\sin[-L'-\Gamma')]=-\sin(L'-\Gamma')$, this yields, at either conjunction or opposition

$$\lambda_{☾}=L'-\frac{15}{4}pe_{☾}\sin(L'-\Gamma')$$

where the sine term represents the angular distance in longitude of the Moon from perigee. If this difference is positive, the Moon is ahead of perigee (i.e., has a greater longitude); if the Moon has a smaller longitude, and the difference is negative, the Moon is behind the perigee position.

Owing to the fact that the correction to the mean longitude is subtractive, the true place of the Moon is ahead of the mean place if the Moon at either of the two syzygies is between apogee and perigee (i.e., $L'-\Gamma'<90°>0°$). The true lunar position is behind the mean position when the Moon at syzygy is between perigee and apogee (i.e., $L'-\Gamma'<180°>90°$).

In the quadratures, the first equation above reduces to

$$\lambda_{☾}=L'+\frac{15}{4}pe_{☾}\sin[2(90°)-(L'-\Gamma')]$$

and, since $\sin[180°-(L'-\Gamma')]=+\sin(L'-\Gamma')$,

$$\lambda_{☾}=L'+\frac{15}{4}pe_{☾}\sin(L'-\Gamma').$$

Because the corrective term is now additive, the true place of the Moon lies ahead of the mean place between perigee and apogee and behind the mean place between apogee and perigee.

If the line of apsides coincides with either the line of syzygies or the line of quadratures (i.e., if one of the lunar apsides occurs simultaneously with the new, first quarter, full, or third quarter moon), the difference between the true and mean longitudes of the Moon becomes zero. The same zero correction applies also when the Sun is midway between the Moon and either apse.

The foregoing analysis relates to the perturbative effect of the lunar evection term alone. It is seen that, at the position of perigee-syzygy, this perturbation function by itself plays no part in altering either the true longitude of the Moon or the difference between the true longitude and the mean longitude thereof. As will be noted later, this is not true, however, of either the eccentricity of the lunar orbit or the instantaneous parallax of the Moon.

In actuality, the influence of the lunar evection produces a significant change in the lunar orbit, as discussed in a preceding section dealing with the astronomical cause of this perturbation. When the effect of the lunar evection is combined with that of the elliptic inequality, the quantitative result is to alter the eccentricity of the lunar orbit by an algebraic factor equal to approximately $\frac{15}{8}pe_{☾}$.

The corrective term, whose complete value is given by the expression $\frac{15}{8}\,pe_{☾}\cos 2(\Gamma'-L)$ is additive if the line of apsides coincides with the line of syzygies, and subtractive if the line of apsides coincides with the line of quadratures. Thus at a time of perigee-syzygy, considering the effect of lunar evection alone, the increased eccentricity of the Moon's orbit $e'_{☾}$ is related to the former, unperturbed eccentricity $e_{☾}$ through the relationship

$$e'_{☾}=e_{☾}\left[1+\frac{15}{8}p\cos 2(\Gamma'-L)\right].$$

Similarly, the perturbational effects of the *lunar variation* may be analyzed as follows:

In the previously given general expression for the longitude of the Moon at any time t, the representation of that part of the Moon's disturbed motion caused by the lunar variation is given by

$$\lambda_{☾}=L'+\frac{11}{8}p^2\sin[(2-2p)L'-2L_0]$$

where the various symbols are as previously defined.

If the Sun's mean longitude at the time t is now represented by L, such that $L=n_{\odot}t+L_0$, and since $p=n_{\odot}/n_{☾}$ or $n_{\odot}=pn_{☾}$, and $L'=n_{☾}t$, the above equation reduces to

$$\lambda_{☾}=L'+\frac{11}{8}p^2\sin 2(L'-L).$$

From this equation, certain interpretations are immediately obvious. When the *difference* between the mean longitudes of the Moon and Sun (the mean elongation) equals 45°, 135°, 225°, or 315°, the additive term in this expression reaches a maximum with its value equal numerically to $\pm\frac{11}{8}p^2$ (plus other higher-order terms for greater accuracy). The value $\frac{11}{8}p^2$ is only a first coefficient. The next is $\frac{59}{12}p^3$. An entire series can be developed, and at least five terms are necessary for comprehensive accuracy. When the mean lunar elongation is 0° or 180° (i.e., at either syzygy), the true longitude of the Moon is equal to its mean longitude and the effect of the lunar variation on change in longitude is zero. At the lunar quadratures, (mean elongation = 90° or 270°), the lunar variation term also reduces to zero and the Moon's true longitude is again equal to its mean longitude.

Between conjunction and a mean elongation of 45°, as the result of the lunar variation alone, the Moon's true longitude lies ahead of the mean longitude by an amount which varies from zero to a maximum. Between elongations of 45° and 90°, the angular amount by which the true moon lies ahead of the mean moon decreases from a maximum to zero. Between elongations of 90° and 135°, and between 135° and 180°, the true position of the Moon (in either longitude or right ascension) lies behind its mean position.

The difference varies in the same manner from zero to a maximum between elongations of 90° to 135° and—between 135° and 180°—ranges back to zero again. Between opposition and conjunction, the same cycle is repeated. Thus, the difference between true longitude and mean longitude varies in repetitive cycles throughout successive octants of the lunar orbit according to the basic pattern shown in figure 34. The effects of these differences upon the length of the tidal day later to be discussed follow the same pattern.

Summary of the Effects of the Principal Lunar Perturbations in Differentiating Between the Mean and True Orbital Positions of the Moon

The following summation is given of four physically perturbing influences whose individual effects can produce a difference between the mean and true places of the Moon.

1. Effects of Elliptic Inequality

From perigee to apogee, the true place of the Moon is ahead of the mean place, considering this cause alone; from apogee to perigee, the true place of the Moon is behind the mean place. At perigee and syzygy, true place will be the same as mean place.

2. Effects of Evection (combined with the elliptic inequality)

The true place of the lunar apse (perigee or apogee) is behind its mean place when the apse lies in either the first or third quadrant ahead of the Sun, and the apse is ahead of its mean place when it lies in the second or fourth quadrant ahead of the Sun. The difference in longitude between apse and Sun is given by

$$\Delta\Gamma'=\frac{15}{8}k\sin 2(\Gamma'-L),$$

with the symbols as previously indicated. When the lunar apse is coincident with the direction of the Sun, the true and mean places of the lunar apse are the same.

3. Effects of Lunar Variation

Between syzygy and quadrature, the true place of the Moon is ahead of the mean place; between quadrature and syzygy, the Moon's true place is behind the mean place. The maximum difference between true and mean place occurs in the octant positions. The relative angular velocities of the Moon at various positions in orbit may also be readily obtained.

The expression for lunar variation given in the last equation of the preceding section is

$$\lambda_{☾}=L'+\frac{11}{8}p^2 \sin 2(L'-L)$$

Since: $L'=n_{☾}t$; $L=n_{\odot}t+L_0$; and $n_{\odot}=n_{☾}p$; then $L=n_{☾}pt+L_0$.

Substituting:

$$\lambda_{☾}=n_{☾}t+\frac{11}{8}p^2 \sin 2[n_{☾}t-(n_{☾}pt+L_0)].$$

Differentiating this equation with respect to t to find the variation in angular velocity of the Moon with position in orbit as the result of this perturbation alone, and thereafter converting back to the original symbols, wherever possible, for nomenclatural consistency:

$$\frac{d\lambda_{☾}}{dt}=n_{☾}+\frac{11}{4}n_{☾}p^2(1-p) \cos 2(L'-L).$$

Hence, at the syzygies, where $L'-L=0$, or 180°, the lunar velocity in orbit reaches its maximum value. At the quadratures, the angular velocity becomes minimum. In the octants, the Moon's velocity is equal to its mean value, $n_{☾}$.

4. Effects of the Annual Equation

In terms of the influence of the annual equation upon lunar position, the principal result is that, between perigee and apogee, the true place of the Moon lies behind the mean place; between apogee and perigee, the true place of the Moon lies ahead of the mean place.

Additionally, however, with regard to a subsequent analysis of lunar catch-up times as these contribute to the production of increased perigean spring tides, another somewhat counterproductive relationship derives from the annual equation. This involves the difference in lunar orbital velocities as affected by the Sun, and is most evident at times of solar perigee and solar apogee. When the Sun is at its closest position to the Earth and Moon (solar perigee), the angular velocity of the Moon in its orbit is the least; with the Sun at its greatest distance (solar apogee), the Moon's angular velocity is the greatest. In view of the comparative magnitudes of the solar forces exerted at these times on the Moon revolving in its orbit, this statement might appear to some extent paradoxical.

Considering the effect of the annual equation totally apart from the other perturbational effects, the solar gravitational attraction exerts a varying influence consistent with the changing distance of the Earth from the Sun throughout the year. In accordance with the inverse-distance relationship of Newton's law, this results in the Sun's greatest gravitational force being exerted upon the Earth (and Moon) when the Earth is situated along the line of aspides of the solar orbit and at its perihelion position. The appropriate equation connecting the two variables $P_{☾}$ and $a_{☾}$ in an undisturbed orbit is:

$$P_{☾}=\frac{2\pi a_{☾}^{3/2}}{k(M_{\oplus}+m_{☾})^{1/2}}$$

where

$P_{☾}$ = the sidereal period of the Moon's revolution around the Earth
π = in this case, the mathematical constant, 3.14159, denoting the ratio of the circumference of a circle to its diameter
$a_{☾}$ = the semimajor axis of the lunar orbit
$M_{\oplus}$ = the mass of the Earth
$m_{☾}$ = the mass of the Moon
k = the Gaussian constant of gravitation, or amount of attraction between two bodies (in this case, the Earth and the Moon) per unit mass, and at unit distance.

As the Moon revolves in its disturbed orbit, the gravitational attraction of $M_{\oplus}$ on $m_{☾}$ changes continuously for many reasons. Among the various normal components of force affecting the Moon's orbit, there are more of negative than of positive value. This fact results inevitably in an average reduction in the force of $M_{\oplus}$ on $m_{☾}$ which, in turn, implies a lessening in the assumed constant value of k. The ensuing increase in $P_{☾}$ with decrease in the value of k according to the above equation results in a lengthening of the lunar month. Such an extension of the lunar month would provide a consistent rule if the Sun's gravitational attraction on the Moon's orbit was itself constant.

However, this inverse variation of $P_{☾}$ with k is valid only for motion which is accelerated from a source of attraction at a constant (unit) distance. The fact that the Earth revolves in an elliptical orbit and varies constantly in distance from the Sun generally invalidates the previous equation and its accompanying increase in period with decrease in k.

Thus, as the Earth moves from perihelion to aphelion and toward greater distances from the Sun, the previous influence of the equation in *increasing* the length of the lunar month is rendered correspondingly ineffectual.

The net result is a relative *decrease* in the length of the lunar month. This, in turn, causes a progressive acceleration in the Moon's daily motion in orbit as the Earth revolves from perihelion to aphelion, and a decrease in the Moon's motion as the Earth revolves from aphelion to perihelion. Because of carry-over effects, the greatest and least lunar velocities (due to this cause alone) occur at the times of aphelion and perihelion, respectively, although the normal components of the Sun's gravitational force on the Moon's orbit are actually zero then. The induced effects of lunar velocity in orbit are, of course, superimposed upon, and vectorially either added to, or subtracted from, the lunar velocity effects produced by the Moon's passage through perigee and apogee, and by other factors.

The expression representing the effect of the annual equation as noted at the beginning of the preceding section is

$$\lambda_{☾}=L'-3pe_{\oplus}\sin(L-\Gamma_0)$$

Because $L'=pt$, and $L-\Gamma_o$ is equal to the mean solar anomaly g, or angular separation of the Sun from perihelion, assuming a uniform motion of the solar line of apsides,

$$\lambda_{☾}=pt-3pe_{\oplus}\sin g$$

Differentiating this equation with respect to the time, to determine the Moon's velocity in orbit as a function of the Sun's mean anomaly:

$$\frac{d\lambda_{☾}}{dt}=p[1-3p^2e_{\oplus}\cos g]$$

Since both p and $e_{\oplus}$ are decimal values, this equation yields the smallest lunar angular velocity from this perturbational cause alone at the solar perigee ($g=0°$), and a value equal to p at $g=90°$. At the solar apogee ($g=180°$), the Moon's velocity reaches its maximum value.

Corrections for Lunar Perturbations as Used in the Tidal Equations

As the result of the previously enumerated deviations in the positions and motions of the Moon produced by perturbations, neither the instantaneous true longitudes of the Moon in its orbit nor its true distance (parallax) with respect to the Earth in the perturbed orbit agree with the corresponding mean values. In tidal computations, this fact results in the use of the following equations relating true and mean longitude and true and mean parallaxes. These approximations of the corresponding astronomical equations are employed in an endeavor to take into account the various lunar perturbations.

Where:

L' = the mean longitude of the Moon, measured in the ecliptic from the mean equinox of date to the mean ascending node of the lunar orbit, and then along the orbit

$\lambda_{☾}$ = the true longitude of the Moon, measured from the mean equinox of date in the same fashion

Γ' = the mean longitude of the lunar perigee

L = the mean longitude of the Sun

$e_{☾}$ = the eccentricity of the Moon's orbit

p = the ratio of the mean daily motion of the Sun to that of the Moon

$\pi_{☾}$ = the *true* geocentric horizontal parallax of the Moon

$\bar{\pi}_{☾}$ = the *mean* geocentric horizontal parallax of the Moon,

the tidal equation relating the mean longitude and the true longitude in the lunar orbit is

$\lambda_{☾}$ (in radians) (true longitude of the Moon)

$=L'$ (mean longitude of the Moon)

$+2e_{☾}\sin(L'-\Gamma')+\frac{5}{4}e_{☾}^2\sin 2(L'-\Gamma')$
(elliptic inequality)

$+\frac{15}{4}pe_{☾}\sin(L'-2(L'-2L+\Gamma')$
(evectional inequality)

$+\frac{11}{8}p^2\sin 2(L'-L)\ .\ .\ .\ .$
(variational inequality)

The corresponding equation relating the ratio of the true and mean parallaxes of the Moon is

$\pi_{☾}/\bar{\pi}_{☾}$

$=1$

$+e_{☾}\cos(L'-\Gamma')+e_{☾}^2\cos 2(L'-\Gamma')$
(elliptic inequality)

$+\frac{15}{8}pe_{☾}\cos(L'-2L+\Gamma')$
(evectional inequality)

$+p^2\cos 2(L'-L)\ .\ .\ .\ .$
(variational inequality)

The astronomical terms involving the effects of annual equation and reduction (from longitude in the ecliptic to longitude in the Moon's orbit) are not included in the foregoing series—nor are higher-order terms in various of the individual perturbations. As will be noted in subsequent chapters, the inclusion of these terms to a higher order of accuracy is necessary in order to ensure a meaningful representation of the lunar motions concerned.

Particularly is this true, for example, in the case of the alternating progression and regression of the position of the lunar perigee. The present computations of this effect assume, at all points in the lunar orbit and at all force-angles with respect to the Sun, a mean daily motion for the lunar perigee of $+0.111404°/^d$. It will be seen in connection with figure 28B that, at the time of a proxigee-syzygy (close perigee-syzygy) situation, the true motion of perigee may exceed $-1.6°/^d$.

Similarly, the *mean* longitude of lunar perigee enters into the tidal equations for determining true longitude and true parallax as affected by the elliptic inequality and the evectional inequality. The appropriate corrections occur only through the term whose coefficient is $\frac{11}{8}\, p^2$. This coefficient is but one of an infinite series. Unless at least four more of these higher-order terms are included, the resulting value of the total angular difference between true and mean longitude is far from accurate.

The aforementioned assumptions and approximations used in this series of corrective expressions for transforming from mean to true longitude and mean to true parallax were adequate for their time. They are still sufficiently accurate to define the more usual tidal circumstances which do not involve, for example, the special combinations of astronomical tide-raising forces and other factors necessary to the production of perigean spring tides. The effects of such amplified forces, the extended intervals of their action, and the perturbative influences which contribute to both, will form the principal subject of the next two chapters.

The nearly phenomenal advances during recent years in high-speed electronic data processing and related technology have rendered possible vastly more complex computational procedures. At the same time, new requirements for even greater precision in certain local tidal predictions have arisen. These have come about as the result of the burgeoning development of coastal communities, the increasing establishment of vacation homesites, beach cottages, and condominiums ever closer to the high waterline, and the expanded and proliferating recreational use of the coastal zone.

Such growing demands make a review of the previous tide-computing methodology both necessary and desirable. As a part of this evaluative process, new techniques and refined computational methods are worthy of consideration. The direction of effort pursued should include an additional emphasis on the tidal characteristics of low-lying, flood-prone localities subject to potentially catastrophic attack from the sea.

Numerous examples of extremely severe property damage and, upon occasion, attendant loss of life, are shown among the previously tabulated instances of coastal flooding produced by perigean spring tides which have occurred in combination with winter storm conditions. This fact points realistically to the need for greater public awareness of the potential hazards existing in connection with this type of tide when accompanied by the appropriate meteorological conditions.

Salient investigations should include special attention to the delineation of factors useful in analyzing, predicting, and gauging the probable intensity of tidal flooding well in advance of such catastrophic events. The factors explored would also involve the determination of those conditions of air-sea coupling most vulnerable to the production of tidal flooding, should the accompanying meteorological conditions of low atmospheric pressure and strong, persistent, onshore winds prevail.

The development of a combined theoretical and empirical basis for effectuating this knowledge will be discussed in the ensuing chapters.

Chapter 4.

Identification of the Specific Astronomical Forces and Influences Contributing to the Production of Perigean Spring Tides

Proceeding progressively toward the problem at hand—that of identifying the physical origins of perigean spring tides, together with the possibility of their subsequent amplification and development—it is now necessary to consider the role played by the interrelationships between various dynamic influences in the production of such enhanced tides. The following three chapters therefore will deal with the consequences of the combination of the various individual factors (positions, motions, forces, and perturbations) enumerated in the preceding three chapters, plus the Appendix.

The Principal Concurrent Tidal Forces

Among the coactive, maximizing, tide-raising influences, those resulting from the astronomical alignments described in the next two sections constitute the most important conjugate factors in the production of perigean spring tides. The concepts which succeed them in the same chapter are equally substantial, but secondary in their influence to these.

The Effects of a Near-Alignment of Perigee and Syzygy in Producing Tides of Increased Amplitude and Range

The production of increased high and low waters at times of perigee-syzygy takes place in consequence of a chain of interrelated events. These are:

(1) The orbital motion of the Moon in an ellipse, subject to the parallax-enhancing effects of the elliptic inequality; (2) The occurrence of a near-coincidence (minimum angular separation) between the positions of perigee and syzygy because of commensurable relationships between the synodic and anomalistic periods of the Moon; (3) Augmented tide-raising forces produced by the combined gravitational attractions of the Sun and Moon at syzygy, and the closer approach of the Moon to the Earth at perigee; (4) An increase in the eccentricity of the Moon's orbit caused by the perturbative actions of lunar evection and variation; (5) As the result of this increase in the eccentricity of the lunar orbit, a further decrease in the perigee distance of the Moon toward a possible proxigee relationship, and an increase in the geo centric horizontal parallax (generally related in amount, to the closeness of the perigee-syzygy separation); (6) Through the reduced distance of the Moon, an increase in the lunar gravitational forces exerted upon the waters of the Earth, thus augmenting the tide-raising forces; and (7) A corresponding increase in the amplitude and range of the tides.

Basic Force Equation Defining the Magnitude of Tidal Uplift

In his monumental five-volume *Manual of Tides* [1] (1898), Rollin A. Harris, formerly chief mathematician in the U.S. Coast and Geodetic Survey, presented a comprehensive treatment of the tide-producing potential. In chapter IV of part II, he included the development of the expression for the height of the tides above the undisturbed sea level as a function of numerous related factors. Carrying this development one step further, an exhaustive analysis of perigean spring tides on the basis of Harris' original equations is included below. The symbols of this earlier treatise have been converted to those used in the present volume for consistency and continuity.

Where:

ΔS = height of the tide above undisturbed sea level
$m_{☾}$ = Moon's mass
$M_{\oplus}$ = Earth's mass
$\rho_{\oplus}$ = Earth's mean radius
$a_{☾}$ = Moon's mean distance from the Earth (equal to the semimajor axis of the Moon's orbit)

$e_☾$ = eccentricity of the lunar orbit

ϕ = geographic latitude of the place of observation

$p = \frac{n_\odot}{n_☾}$ = ratio of the mean angular daily motion of the Sun to that of the Moon (=0.0748)

${}_q\alpha_I$ = difference in right ascension of the extremity of the x-axis of the coordinate reference system used, measured along the celestial equator from the northward-crossing point of intersection between the lunar orbit and the celestial equator

${}_oL'_I$ = difference in the Moon's mean longitude, measured in the lunar orbit from its northward crossing point of intersection with the celestial equator

${}_cL'_♈$ = mean longitude of the Moon, measured in the ecliptic from the mean equinox of date to the mean ascending node of the lunar orbit, and then along the orbit

${}_cL_♈$ = mean longitude of the Sun, measured (in the ecliptic) from the mean equinox of date

${}_c\Gamma'_♈$ = mean longitude of the Moon's perigee, measured in the ecliptic from the mean equinox of date

I = angle of inclination between the lunar orbit and the celestial equator

$u = \cos \frac{1}{2} I$

$v = \sin \frac{1}{2} I$

Terms in **X**, **Y**, and **Z** will be defined below.

If the value of ΔS represents the theoretical height of the tides produced, subject to a given combination of circumstances and perturbations involving the Sun and Moon, the appropriate equation for this tidal height is

$$\Delta S = \frac{3}{2}\frac{m_☾}{M_\oplus}\left(\frac{\rho}{a_☾}\right)^3 \frac{\rho}{(1-e_☾{}^2)^3}\left[\frac{1}{2}\cos^2\phi(\mathbf{X}^2-\mathbf{Y}^2) + \sin 2\phi\mathbf{XZ} + \frac{3}{2}\left(\frac{1}{3}-\sin^2\phi\right)\frac{1}{3}(\mathbf{X}^2+\mathbf{Y}^2-2\mathbf{Z}^2)\right] \quad (1)$$

where a typographical correction has been made in the first $\mathbf{Y}^2$ (from $\mathbf{Y}^3$ in Harris' report).

The equations which represent the effects of lunar evection are

For semidiurnal tides:

$$\mathbf{X}^2-\mathbf{Y}^2 = \frac{105}{16} p e_☾ u^4 \cos(2{}_q\alpha_I - 2{}_oL'_I - {}_cL'_♈ + 2{}_cL_♈ - {}_c\Gamma'_♈) \quad (2)$$

$$-\frac{15}{16} p e_☾ u^4 \cos(2{}_q\alpha_I - 2{}_oL'_I + {}_cL'_♈ - 2{}_cL_♈ + {}_c\Gamma'_♈) \quad (3)$$

For diurnal tides:

$$\mathbf{XZ} = -\frac{105}{16} p e_☾ u^3 v \sin({}_q\alpha_I - 2{}_oL'_I - {}_cL'_♈ + 2{}_cL_♈ - {}_c\Gamma'_♈) \quad (4)$$

For fortnightly tides:

$$\frac{1}{3}(\mathbf{X}^2+\mathbf{Y}^2-2\mathbf{Z}^2) = \frac{1}{3}(u^4-4u^2v^2+v^4)\frac{45}{8} p e_☾ \cos({}_cL'_♈ - 2{}_cL_♈ + {}_c\Gamma'_♈) \quad (5)$$

The equations representing the effects of lunar variation are

For semidiurnal tides:

$$\mathbf{X}^2-\mathbf{Y}^2 = \frac{23}{8} p^2 u^4 \cos(2{}_q\alpha_I - 2{}_oL'_I - 2{}_cL'_♈ + 2{}_cL_♈) \quad (6)$$

For diurnal tides:

$$\mathbf{XZ} = 0 \quad (7)$$

For fortnightly tides:

$$\frac{1}{3}(\mathbf{X}^2+\mathbf{Y}^2-2\mathbf{Z}^2) = \frac{1}{3}(u^4-4u^2v^2+v^4)3p^2 \cos(2{}_cL'_♈ - 2{}_cL_♈) \quad (8)$$

A close analysis, term by term, of the foregoing general equation (1) for tidal height will reveal the effect of a perigee-syzygy alignment in producing augmented high tides, principally through the perturbations associated with lunar evection and lunar variation. The effects of the individual expressions involving these two perturbative influences will be evaluated first, and the results will then be combined in the general equation.

1. Lunar Evection Effects

(a.) The first analysis will begin with the term at the extreme left of the parentheses in equation (2) and then proceed toward the right.

The term ${}_q\alpha_I$ involves a rectangular coordinate system whose origin is at the center of the Earth and whose z-axis is coincident with the Earth's axis of rotation. The x- and y-axes are mutually perpendicular thereto and are located in the plane of the Earth's Equator. The angle ${}_q\alpha_I$ represents the position of the extremity of the x-axis, measured as a difference in right ascension along the celestial equator from the point of intersection of the lunar orbit with the celestial equator. (The latter origin is assumed to move only as the equinox moves, due to precession. This westward motion of the celestial equator along the ecliptic also shifts the lunar intersection point along the celestial equator.)

The continuous increase in the value of ${}_q\alpha_I$ through 24^h (or 360°) of right ascension each day is an indication of the eastward movement of the end-point of the x-axis along the celestial equator. This rectangular coordinate system is tied to, and the motions of the x- and y-axes are a function of, the rotating Earth.

The x-axis as selected will intersect the geographic longitude of the place of observation on the Earth's surface. As this x-axis rotates with the Earth through 360° once in each 24^{msh}, it passes through all possible values of right ascension or celestial longitude, whereas the Moon's mean longitude increases by only 13.176396°/day due to its orbital motion.

Because the effect of tidal forces in producing the exceptionally high waters of perigean spring tides is under consideration, the concepts of the phase and parallax lags must later be introduced in determining the exact dates of the maximum tides. However, on any one date, the high tides will necessarily occur with the Moon close to the position of the upper or lower meridian of the place (i.e., subject only to the lunitidal interval and, at open seacoast locations, usually within an hour or so of meridian transit of the Moon).

The existing mean longitude of the Moon will, therefore, be at a point near the local meridian, while the x-axis of the coordinate system under discussion passes through the geographic location of the observer.

Although all symbolic values are initially as defined in the above legend, through the introduction of the transformation equations $p = \cos \frac{1}{2}I$ and $q = \sin \frac{1}{2}I$ in the reductions necessary for equations (1)–(8), the value of ${}_q\alpha_I$ has been projected from the equatorial plane into that of the Moon's orbit. Hence, the direct subtraction of L_I' from ${}_q\alpha_I$ is possible as indicated in the various equations.

As, subject to the Earth's rotation, the longitude of the observer's position approaches and transits the meridian, the difference between $2_q\alpha_I$ and $2_oL_I'$ will become successively smaller and, on the meridian, as ${}_q\alpha_I$ and ${}_oL_I'$ become equal, will converge on 0°. Since $\cos 0° = 1$, this circumstance contributes its maximum additive influence to the resulting height of the tides.

One further factor—although a somewhat academic one because of the small angles involved—serves also to decrease the angular difference between ${}_q\alpha_I$ and ${}_oL_I'$ as the Moon approaches perigee-syzygy and thus increase the value of the cosine function to a near-maximum. This is the effect of the Moon's varying speed in orbit.

The actual longitude value of ${}_q\alpha_I$ may be either smaller than ${}_oL_I'$ (before catch-up therewith at perigee-syzygy) or larger (following perigee-syzygy). The difference ${}_q\alpha_I$ minus ${}_oL_I'$ at any time represents the faster angular motion of the rotating Earth in catching up on the Moon revolving in orbit. Prior to perigee-syzygy, the greater value of $2_o\alpha_I$ is closing continuously on $2_oL_I'$, but at a slightly lessening rate.

Since, to the accuracy required in tidal predictions, the angular velocity of the rotating Earth (affecting the value of ${}_q\alpha_I$) does not vary, any *rate of change* affecting the instantaneous difference between $2_q\alpha_I$ and $2_oL_I'$ can be a function only of the Moon's changing velocity in orbit.

As the Moon approaches perigee-syzygy, its angular velocity increases as the result of Kepler's Law. The value of $2_oL_I'$ will also increase at a slightly faster rate. The ensuing situation involves the subtraction of a larger positional angle (being swept through at a slightly increasing angular velocity) from a smaller positional angle (being swept through at a constant rate). Accordingly, as the Moon's velocity increases, the instantaneous value of the difference $(2_q\alpha_I - 2_oL_I')$ changes less rapidly. During this period, the angular difference $(2_q\alpha_I - 2_oL_I')$ will, therefore, be reduced by a steadily increasing, but decimally small amount (with a negative angle resulting from the subtraction). The value of the cosine function of the total expression in parentheses in equation (2) is increased in proportion (although its value is so near unity, the effect acts more to extend the period close to perigee-syzygy and to prolong this period of maximum tide-raising influence than to increase the tidal amplitude).

As the Moon, Sun, and lunar perigee come into alignment at perigee-syzygy, ${}_cL'_♈ = {}_cL_♈ = {}_c\Gamma'_♈$. Therefore, grouping the last three terms contained within the parentheses, $-{}_cL'_♈ - {}_c\Gamma'_♈ + 2{}_cL_♈ = 0$, and the difference between $2_q\alpha_I$ and $2_oL'_I$ remains the only significant factor left inside. Since this difference is a negative angle prior to perigee-syzygy, it lies in the fourth trigonometric quadrant, where the cosine is positive.

Because, at perigee-syzygy, this difference amounts to only a small increment above the value of cos 0° produced by the cancellation of the other terms, the cosine of the total function in parentheses will be only very slightly less than its maximum possible value, +1. This maximum possible value of the cosine function ensures a full application of the constant terms and variable coefficients by which it must be multiplied to evaluate the entire first expression for $\mathbf{X}^2 - \mathbf{Y}^2$ in the case of semidiurnal tides. Attention will now be given to these various coefficients and constants.

It has been seen in a previous section that, at perigee-syzygy, and as the result of lunar evection, the eccentricity $e_☾$ of the lunar orbit always increases. At the same time, $\frac{105}{16}$ and p are constants, and the value of u is a decimal taken to the fourth power and is always very small. Therefore, subject to the conditions of perigee-syzygy, *all factors in the first part of the equation for* $\mathbf{X}^2-\mathbf{Y}^2$, *the semidiurnal portion of the total evection term, contribute their maximum values toward raising the height of the resulting perigean spring tides.*

(b.) The second expression (3) in the semidiurnal portion of the total equation for the effect of lunar evection is algebraically subtractive. However, being preceded by the coefficient $\frac{15}{16}$, which is only 1/7th part of the numerical coefficient $\frac{105}{16}$ in the first expression (2), it represents but a small decrease in the value of this first expression.

The last three terms in the parentheses of equation (3) are identical (with reversed algebraic signs only) to those in the first expression (2) and, at perigee-syzygy, the algebraic sum of these terms is 0°. Likewise, in taking the difference between $2_q\alpha_I$ and $2_oL'_I$—the first two terms in the parentheses—the difference is still negative, and decreasing in numerical value with approach to perigee-syzygy. In evaluating the cosine function, as well as the effects of p, $e_☾$, and u, the same general results apply (although with only 1/7th the total value) as those deduced from the first expression.

Thus, at times of perigee-syzygy, *the net result of the combined expressions (2) and (3) associated with lunar evection serves to increase the height of the semidiurnal tides.*

(c.) In the expression (4) for the effect of the lunar evection upon the diurnal type of tides, a sine function rather than a cosine function is involved. As in the expressions for the evectional effect on the semidiurnal tides, the algebraic sum of the terms within the parentheses is very small. The second term $2_oL_I'$ is, however, approximately twice the magnitude of the first, $_q\alpha_I$, resulting in a somewhat larger value of their small individual difference. Although the effect of the lunar evection on diurnal tides thus acts in an opposite direction—to decrease the height of these tides—the result of this sine function, when multiplied by the constants $\frac{105}{16}$ and p, and the small variable quantities $e_☾$, u^3, and v is still quite small. *This subtractive quantity will, however, prove to be of some importance in connection with a subsequent discussion of the lesser effect of perigee-syzygy upon the diurnal type of tides.*

(d.) Finally, the influence of lunar evection upon the fortnightly type of tides in equation (5) is seen to be positive, additive, and to contain a cosine function as in the case of semidiurnal tides. The terms in parentheses again cancel out at perigee-syzygy, and cos 0° reaches its maximum value. The remaining factors $\frac{1}{3}$, $\frac{45}{8}$, 4, and p are constants, and $e_☾$, u, and v are small positive variables. Since the sum of the values u^4 and v^4 will always be larger than the term $-4u^2v^2$, *all terms in the expression for the effect of lunar evection on the fortnightly type of tide thus contribute toward increasing this type of tide at times of perigee-syzygy. However, the fortnightly constituents of the tide are not of major consequence.*

2. Lunar Variation Effects

The analysis of the effects of lunar variation upon the heights of semidiurnal, diurnal, and fortnightly tides can proceed in exactly the same way from equations (6)–(8) above.

(a.) Within the parentheses of equation (6), the values of the terms $2_q\alpha_I$ and $2_oL_I'$ are exactly the same as in the case of semidiurnal tides which are subject to lunar evection. The difference between these terms is also negative as before, and increases numerically with approach to perigee-syzygy. In the present case, the terms $-2_cL'_♈$ and $+2_c\Gamma'_♈$ exactly cancel out at perigee-syzygy, leaving the cosine of 0° and whatever small negative difference is represented by $2_q\alpha_I$—$2_oL_I'$. Again, the cosine of this small negative angle (in the fourth quadrant) yields a result for the cosine function which is very nearly the maximum possible value.

Both the fraction $\frac{23}{8}$ and the symbol p^2 are constants, and the coefficient u^4 is numerically very small. Accordingly, at a time of perigee-syzygy, *all terms in this equation contribute to an increased value of the semidiurnal term* X^2-Y^2 *corresponding to the effects of lunar variation.*

(b.) As noted, the effect of lunar variation on the diurnal tides, represented by the term **XZ**, is zero.

(c.) Finally, there remains the influence of the lunar variation upon the fortnightly tides, given by the expression $\frac{1}{3}(\mathbf{X}^2+\mathbf{Y}^2-2\mathbf{Z}^2)$. In this equation it is obvious that, at a time of perigee-syzygy, the terms $+2_cL_♈'$ and $-2_cL_♈'$ cancel out, leaving cos 0° as the cosine function, and the maximum possible value of unity for this part of the expression.

Since the factors $\frac{1}{3}$, 4, 3, and p are all constants, and since u^4 and v^4 are always positive and their sum $> -4u^2v^2$, this part of the total expression also is always positive, and increasing as the value of either u or v increases.

Thus, lunar variation also contributes toward increasing the fortnightly component of the tides at a time of perigee-syzygy.

3. Summary Analysis

It now becomes important to see how these various tidal components, as affected by lunar evection and lunar variation, provide a sensible increase in water level to create perigean spring (and, upon certain occasions later to be discussed, proxigean spring) tides. For this, it is necessary to go back to the original, full-length equation (1) of which these three types of tides form a part.

(a.) In a procedure opposite to that used for the separate components of each expression, analysis will begin with the last expression in the series and move toward the first. The expression in $\mathbf{X}^2+\mathbf{Y}^2-2\mathbf{Z}^2$ representing the fortnightly components already has been seen to be at its maximum value at perigee-syzygy as the result of both the lunar evection and lunar variation. The constants $\frac{3}{2}$ and $\frac{1}{3}$ in this last expression will not decrease its maximum value. The remaining function $\left(\frac{1}{3}-\sin^2\phi\right)$ is a function of the latitude of the tide station. As the value of ϕ increases, the value of the term in parentheses decreases, so that the effect of the entire expression is to increase the tide heights at perigee-syzygy to a greater extent at low latitudes, with a maximum value at the Equator.

(b.) Returning to the second expression in the series for ΔS—that indicating the contribution of diurnal tides—it was found earlier that, in the case of lunar evection, the effect was to reduce the height of the diurnal component of the tides very slightly at a time of perigee-syzygy. The presence of the lunar variation exercises no influence at all upon the height of the diurnal tides.

(c.) Contrastingly, and by no means last in importance, there is the contribution to the increased height of the tides at time of perigee-syzygy provided by the semidiurnal component. As will be revealed in subsequent tide-curve analyses, this component is actually that most significant to the technical concepts of this work.

The function $\mathbf{X}^2-\mathbf{Y}^2$ was seen, in connection with both the lunar evection and lunar variation effects, to exercise an influence in augmenting the height of the tides at times of perigee-syzygy. The immediately preceding factor, $\frac{1}{2}\cos^2\phi$, is a function of the geographic latitude and, as in a similar case for the fortnightly tides, implies an increasing effect on tide levels with lower latitude, becoming maximum at the Equator.

Finally, there remain common multipliers for all three expressions, involving the constants 3/2, $m_☾$, $M_\oplus$, and ρ_s, and the parameters $a_☾$ and $e_☾$, which are variable because of perturbational effects. Since all of the constants have positive values, providing additive influences, only some major variability in $a_☾$ or $e_☾$ could conceivably produce a downward adjustment in tide heights, or subtract from the enhanced tides produced by the other factors in the tidal equation.

Both $a_☾$ and $e_☾$ increase at a time of perigee-syzygy. The magnitude of $a_☾$ becomes dynamically greater due to the perturbations introduced by changing tangential forces as the Moon attains a greater velocity in orbit (its maximum is at perigee-syzygy) and as the value of $a_☾$ itself increases.[2]

Where:

$\mathbf{V}_☾$ = the velocity of the Moon in orbit

k^2 = the universal (Gaussian) constant of gravitation

$M_\oplus$ = the Earth's mass

$m_☾$ = the Moon's mass

$r_☾$ = the radius vector, or instantaneous distance of the center of the Moon from the center of the Earth

$a_☾$ = the semidiameter of the Moon's orbit

Then:

$$\mathbf{V}_☾=k^2(M_\oplus+m_☾)\left(\frac{2}{r_☾}-\frac{1}{a_☾}\right)$$

and the expression for rate of change caused by the tangential force $\mathbf{T}$ exerted on the Moon's orbit is

$$\frac{\partial a}{\partial \mathbf{T}}=\frac{\partial a}{\partial \mathbf{V}}\frac{\partial \mathbf{V}}{\partial t}=\frac{2a_☾{}^2\mathbf{V}_☾}{k^2(M_\oplus+m_☾)}\frac{\partial \mathbf{V}}{\partial t}$$

which bears out the above statement concerning the direct variation of $a_☾$ with $\mathbf{V}_☾$ and with its own changing value.

Both $a_☾$ and $e_☾$ reach a maximum due to the effects of lunar evection at the time of perigee-syzygy. The Moon also reaches its distance of closest monthly approach, $q_☾$, to the Earth at perigee. This fact is expressed in the relationship

$$q_☾=a_☾(1-e_☾).$$

Although the eccentricity of an ellipse in theory might assume any value from 0 (a circle) to 1 (a straight line), in the case of the Moon its average value is 0.05490. The value of the eccentricity of the lunar orbit does, however, increase at a time of perigee-syzygy, as explained in the earlier descriptive section dealing with the evectional perturbation. It may be seen from any number of actual observations, or from tabular data appearing in *The American Ephemeris and Nautical Almanac*, that the value of $q_☾$ becomes less at perigee-syzygy. The only remaining uncertainty, therefore, is an order-of-magnitude determination of the corresponding effect of perigee-syzygy on the value of $a_☾$.

Using the data in this ephemeris, a representative value of $q_☾$ (in units of Earth-radii) at a time of perigee-syzygy is given as 55.877. From the preceding equation, substituting a value of $e_☾$ slightly greater than its mean value in order to allow for the accretional effect of perigee-syzygy, and giving $q_☾$ its above representative value, it is apparent that, throughout an allowable range of $e_☾$, the corresponding value of $a_☾$ will always come out in excess of $q_☾$.

Since the value of $a_☾$ is always very much larger than that of $e_☾$, the relative influence of the two terms in raising the level of the tides at perigee-syzygy will be obvious by returning to the general equation (1) previously given. Here the factors containing $a_☾$ and $e_☾$ are of the form

$$\left(\frac{\rho}{a_☾}\right)^3$$

and

$$\frac{\rho}{(1-e_☾^2)^3},$$

where both appear in the denominators of fractional terms. The fraction containing the much larger value of $a_☾$ in the denominator, when cubed, will always be far less than the term $1-e^2_☾$ (containing the small decimal value of $e_☾$) when this term in the denominator of the second fraction is cubed. *Hence, the increase in $e_☾$ at perigee-syzygy is far more effective in raising the tides than the increase in $a_☾$ is in reducing them.*

In summation, the combined, net effect of all factors associated with both lunar evection and lunar variation at the time of perigee-syzygy is to raise the level of the tides—particularly those of the semidiurnal and fortnightly types. The only small exceptions occur, as seen above, in the effect of the lunar variation upon diurnal tides and, to an unimportant degree, the effect of the second subtractive expression in the case of semidiurnal tides.

The Effect of Perigee-Syzygy Alignment in Increasing the Value of the Lunar Parallax

The varying monthly distance of the Moon from the Earth which results from the revolution of the Moon in an elliptical orbit (and from certain dynamically induced changes in the major axis of this orbit) has been seen in chapter 3 to be measured in astronomy by a quantity known as the *equatorial horizontal parallax* (π). In brief review, this is defined as the angle (fig. 41) subtended, at the distance of the Moon, by the Earth's equatorial radius. As in the case of any object viewed at a distance, the smaller is the angle subtended, the farther away is the object; conversely, the larger is the parallax angle, the closer the Moon is to the Earth. The conditions creating the maximum value of the Moon's geocentric horizontal parallax and its closest possible approach to the Earth are shown in this same figure.

In the last three equations of chapter 3, the effects of the three terms involving the elliptic, evectional, and variational corrections to the lunar orbit were all shown as adding their near-maximum increments to the mean value of π. This occurs whenever the angular differences between the longitudes of the Sun, Moon, and lunar perigee are close to zero (i.e., at the position of perigee-syzygy).

At the time of perigee-syzygy, the values of L', Γ', and L are all very nearly the same. Hence, the trigonometric differences $L'-\Gamma'$ and $L'-L$ in these parallax equations are equal to zero and, since cosine terms are involved in both cases, the resulting corrections for the elliptic inequality and the variational inequality reach their maximum additive values. Similarly, the value of $(L'+\Gamma')-2L$ is also equal to zero, and again the cosine function provides a maximum additive value, this time for the evectional inequality.

It will now prove meaningful to analyze the quantitative extent of these various corrections, and the actual amount of change in the value of π resulting from their use. Therefore, taking the value of the mean horizontal parallax (transformed into seconds of arc) as a base, and converting the coefficients $e_☾$, $m_☾$, and $\frac{15}{8}$ in the successive additive terms from their indicated radian equivalents to seconds of arc, a new equation for the actual or true parallax is set up.

The terms involving $L'-\Gamma'$ reduce to a single term in mean anomaly, and the angular difference $L'-L$ becomes the Moon's elongation from the Sun. In terms of the corresponding symbolic quantities to be defined below, the equation (with higher-order terms omitted) which expresses, in seconds of arc, the angular value of the Moon's equatorial horizontal parallax π as a measure of its distance from the Earth at any time is:[3]

$$\pi''_☾=3{,}422.608''+187''\cos M+10''\cos 2M$$
$$+34''\cos(2D-M)+28''\cos D+\ldots.$$

In this equation:

$\pi_{☾}$ = the true parallax of the Moon. $M = n_{☾}t$ represents the *mean anomaly*, or angular separation in celestial longitude between the mean moon and the position of mean perigee. D is the angular separation (elongation) in celestial longitude between the mean moon and the mean sun (i.e., the angular difference between their respective mean longitudes).

At the Moon's position of alignment with the Earth and Sun at new moon or full moon, the elongation is 0° or 180°, respectively; at first or third quarter moon, it is approximately 90°.

In the case of both M and D, increasing positive angles in celestial longitude are measured eastward along the ecliptic (counterclockwise as viewed from the north pole of the ecliptic). The mean longitude of the Moon is measured in the ecliptic from the mean equinox of date to the mean ascending node of the lunar orbit, and then along the orbit.

Except for the effect of certain higher-order terms omitted in the above series, the distance of the Moon from the Earth is seen to decrease for all conditions in which the angles M and D become small. The several parallactic terms will now be individually considered.

1. Effect of the Elliptic Inequality

In the above total expression for lunar parallax, the second and third periodic terms ($187''$ cos M and $10''$ cos $2M$) are called the *elliptic terms,* since they are a function of the Moon's motion in an ellipse, as well as the angular distance of the Moon at any time from the position of mean perigee in this ellipse (without any regard to the lunar phase angle). With the approach of the Moon to perigee, the angle M decreases, and each of the two cosine terms increases accordingly. At $M=0°$, these two terms add their maximum possible numerical increments ($187''$ and $10''$, respectively) to the parallax.

2. Effect of the Lunar Evection

Similarly, in the above equation, the term $34''$ cos $(2D-M)$ is known as the *lunar evection*. Whenever the Moon is at perigee, $M=0°$, and, providing the corresponding value of D is not 45° or 135°, E. or W., some positive increment is then always added to the Moon's parallax by this term. If the Moon at either new or full phase ($D=0°$ or 180°) is coincidentally passing through the position of perigee ($M=0°$), the cosine of the evection term reaches its maximum value, increasing the parallax by $34''$. Even close to $M=0°$, the parallax correction is nearly maximum (with $D=0°$), since the cosine of a small negative angle in the fourth quadrant is still very nearly +1.

It is the lunar evection term that is the most complex in the interpretation of parallax additions, since this term involves the simultaneous positions of the Sun, the Moon, and lunar perigee. For example, because cos 188° = −1, the fourth term is subtractive and the Moon's distance from Earth is increased only by the remaining terms at first or third quarters ($D=90°$, E. or W.) when the Moon is simultaneously at perigee ($M=0°$). Either of these positions is called perigee-quadrature. At positions between $D=0°$ and $D=45°$, E. or W., and $D=135°$, E. or W., and 180°, with the Moon also at perigee, the lunar parallax is either decreasing or increasing in accordance with whether the Moon is receding from or approaching syzygy. Between $D=45°$ and $D=90°$, E. or W., and $D=90°$ and $D=135°$, E. or W., with the Moon at perigee, the same relationship holds as in the previous sentence, but with the parallax increasing with lunar recession from syzygy, and decreasing with approach thereto.

For completeness, it must also be noted that when either new moon ($D=0°$) or full moon ($D=180°$) occurs independently of perigee, some increment is added to the parallax provided that M is not 90°. However, the parallax increases to a maximum value as M decreases toward 0° or increases toward 180°.

The effect of evection on the lunar orbit is temporarily to increase its eccentricity about 20 percent whenever the Sun crosses the line of apsides of the Moon's orbit (or approximately 40 percent at the times of near-coincidence of perigee and syzygy). Both the lunar perigee distance decreases (parallax becomes larger) and the apogee distance increases (parallax becomes smaller) under these conditions. In a geometric relationship similar to that distinguishing between the manner of production of spring tides and neap tides (although enhanced perigean forces are also involved in the present case), at perigee-quadrature or apogee-quadrature the eccentricity of the lunar orbit and parallax of the Moon are correspondingly decreased. (See figs. 26A and 26B.)

3. Effect of the Lunar Variation

The cosine term in D alone is known as the *lunar variation*. It is a function entirely of the lunar elongation, or angular separation in longitude of the Moon from the Sun. Its presence in the above expression for parallax is to cause the Moon's parallax to increase by a maximum of $28''$ (and the Moon's distance from the Earth to become correspondingly less) at both new and full phase, with a minimum addition to the parallax at first or third quarter. The addition to the parallax from this cause therefore varies directly from 28″ at new moon to 0″ at first quarter, to 28″ again at full moon, to 0″ at third quarter; and to 28″ once more at new moon. No further complexities are involved.

4. Summary Analysis

It is seen that several different lunar parallactic factors can contribute toward reducing the distance of the Moon from the Earth at the time of a near-simultaneous alignment of either the new moon or full moon with perigee in the condition known as perigee-syzygy. In general, an increasingly larger increment must be added to the base value of the lunar parallax the smaller is the elongation angle between Moon and Sun and/or the closer is the alignment (i.e., the smaller is the difference in time) between perigee and syzygy.

All of the preceding maximum increases in parallax result from the near-alignment of, and the reinforcing gravitational forces exerted by, the Earth and Sun upon the Moon's orbit at these times of perigee-syzygy. Such gravitational reinforcements are seen to be a function of the smallness of (1) the lunar anomaly and (2) the lunar elongation; and, especially, a very small difference between the angles (1) and (2). Practically speaking, the separation-angle between the line of force action joining the Sun, Earth, and Moon (line of syzygies) and the perturbed major axis (line of apsides) of the Moon's orbit can attain a value as small as 6 minutes in time. This happened, for example, in the perigee-syzygy alignment of 1931 March 4 (G.c.t.).[4]

The actual dynamic effect of the combined gravitational forces produced by such a near-alignment between perigee and syzygy is to increase the eccentricity of the Moon's orbit around the Earth. Since the perigee distance q of a celestial object moving in an elliptical orbit is related to the eccentricity e of the orbit through the relationship $q=a(1-e)$, as e increases, q always decreases, for the reasons enumerated in the immediately preceding section. When perigee and syzygy occur at very nearly the same time, the eccentricity of the Moon's orbit increases, and the value of q decreases in proportion. The Moon's perigee distance from the Earth diminishes accordingly. This will later be seen to be the cause of the situation described in this volume as *proxigee-syzygy.*

Two corollary factors are significant in relation to a circumstance to be reviewed quantitatively in chapter 5. At the time of perigee-syzygy, when the differences between these various alignment-angles become zero, the corrective terms necessary to convert from mean parallax to true parallax simultaneously attain their maximum values. The practical consequence is that *the differences between true parallax and mean parallax also reach their greatest values at times of perigee-syzygy.*

Furthermore, a second circumstance provides reinforcement to a basic precept which appears variously throughout this treatise. The longer the period of time during which the angular differences between these respective orbital positions remain near zero, the greater will be the length of time in which the angular additions to the lunar parallax remain at their maximum values. The fact that the Moon, the perigee position in its orbit, and the Sun are all apparently moving in the same direction acts to favor such an extension in time.

The comparative rates of daily angular motion affecting the positions of the Moon, Sun, and lunar perigee are important in this regard. The mean daily motion of the Moon in longitude ($13.176396°/^d$) is far greater than that of the Sun ($0.985647°/^d$), and the mean daily motion of the Moon is far greater than the mean daily motion of perigee ($+0.111404°/^d$).

Summarizing the preceding numbered subsections—at times of perigee-syzygy, two distinct contributions toward the amplification of the tides result from the particular influence of solar perturbations upon the lunar orbit. These are: (1) an increase in the lunar parallax, and a corresponding decrease in the lunar distance from the Earth, thus augmenting the gravitational forces acting on the tidal waters; and (2) a lengthening of the period of time within which these augmented tidal forces can act.

The two concepts cited provide widespread practical support to a basic theory of tidal reinforcement. In a variety of forms, but always involving the combination of (1) increased magnitude and (2) increased duration of gravitational forces, they will find repeated mention throughout this volume in connection with the amplification of perigean spring tides.

At this point in the discussion, while considering factors relevant to item 2, it is important to note the greater length of time within which the Moon will be close to alignment with the position of perigee if the respective *true motions* of the Moon and perigee, rather than their *mean motions,* are considered.

Several of the effects resulting from the substitution of mean motions for true motions in tidal calculations will form the subject of the section immediately following. (Note carefully the distinction between mean *motions* and mean *positions,* since the latter may be more readily determined and adjusted.) The values adopted for various mean daily angular motions are given in part II, chapter 2.

The Concepts of Mean Motion vs. True Motion in Relation to the Earth, Moon, and Lunar Perigee

The differences between true motion and mean motion as these affect various aspects of the gravitational interrelationships between Earth, Moon, and Sun are clearly shown in four of the ensuing diagrams. Each diagram illustrates a particular phase of positional inaccuracy resulting from these assumed average motions.

1. The True Motion of Lunar Perigee

Figure 28A is a plot of the motion of the true position of lunar perigee in units of right ascension during a period of slightly more than 1½ calendar years. These positions of perigee were obtained from the positions of the Moon itself in *The American Ephemeris and Nautical Almanac.* The lunar positions were chosen for the exact times of perigee as tabulated in this same ephemeris. Since, at the time of perigee, the Moon must necessarily occupy this exact position in orbit, the tabulated right ascension of the Moon corresponding to the tabulated time of perigee must also be the position of perigee.

When these successive positions of perigee, one anomalistic month apart, are plotted against the dates of occurrence of perigee, and a smooth trace is made through the resulting data-points, the sinuous curve of figure 28A is obtained. This illustrates clearly that the position of perigee oscillates back and forth, fulfilling one complete cycle of curve undulation in each 6.25–7.5 month period.[a] The curves thus traced consistently show a point of inflection and an enhanced, average forward motion of perigee corresponding to each case of extremely small perigee-syzygy separation-interval. At these times, the position of the juxtaposed event (representing the Sun, Moon, and perigee aligned in very nearly the same right ascension) occurs exactly halfway along that portion of the curve having the least curvature and whose values are increasing in right ascension with increase in time. The period from one perigee-syzygy to the next is approximately the anomalistic month of 27.6 days, but is quite variable between those months which are respectively close to, and removed from, perigee-syzygy. (See fig. 28A.)

At the same time that the intramonthly and intermonthly positions of perigee are oscillating back and forth in right ascension, the average position of perigee as represented by the curve as a whole is moving progressively forward (toward increasing values of right ascension) throughout the course of the year. It is from this net forward movement averaged over a long period of time that the adopted mean daily motion of perigee (amounting to $+0.111404^\circ/^d$) has been derived.

However, the instantaneous, true angular velocity of the lunar perigee is extremely variable and attention already has been drawn to the relationship between its changing velocity and the apparent position of the Sun. This is a perturbational effect, and comes about as a result of the dynamic influence of the Sun upon the Moon's orbit.

2. Short-Period and Long-Period (Averaged) Perturbational Motions of Perigee

Figures 28A, 30, 32, and 33—which are based on the *average* true motion of perigee during several successive anomalistic months—point to the necessity for applying a rigorous analytic solution to define the direction and amount of this motion at any one instant of time. The purpose is to isolate those perturbational effects of shorter period occurring during a single monthly revolution of the Moon. During such smaller intervals of time, the motion of perigee may be either retrograde or direct as it is intermittently over longer intervals, but the predominant (and hence also the *net*) motion of perigee is direct over any extended period.

The above-mentioned diagrams are plotted using the times of perigee (and either the corresponding right ascensions or celestial longitudes of the Moon and Sun) interpolated from *The American Ephemeris and Nautical Almanac.* In this process, the positions of the Moon and Sun expressed in either of these coordinates for the time of perigee are obtained directly from the tabulated time of perigee. By definition, the positions of the Moon and perigee at the time indicated for the Moon's passage through perigee must be one and the same. However, such a graphical delineation as here represented showing the ensuing motion of perigee based on successive monthly returns of the Moon to this position involves only an interpolation by monthly intervals.

Although this procedure is sufficiently accurate to indicate, as a composite picture, the alternating direct and retrograde motions of perigee during several successive months and throughout the course of the year, the number

[a] The commensurability between the anomalistic and synodic months is such that, once a very close alignment of perigee-syzygy has occurred, the next comparably close (nonconsecutive) alignment will be either 6.25–6.50 or 7.25–7.50 synodic months later. The exact period depends upon the sequential arrangement and separation-intervals of intervening cases of perigee-syzygy and the varying lengths of the interposed anomalistic and synodic months (see ch. 6, table 17). If the first extremely close alignment of perigee-syzygy occurs at full moon, the next will occur at new moon; thereafter, the phase will alternate in each succeeding set of such close alignments.

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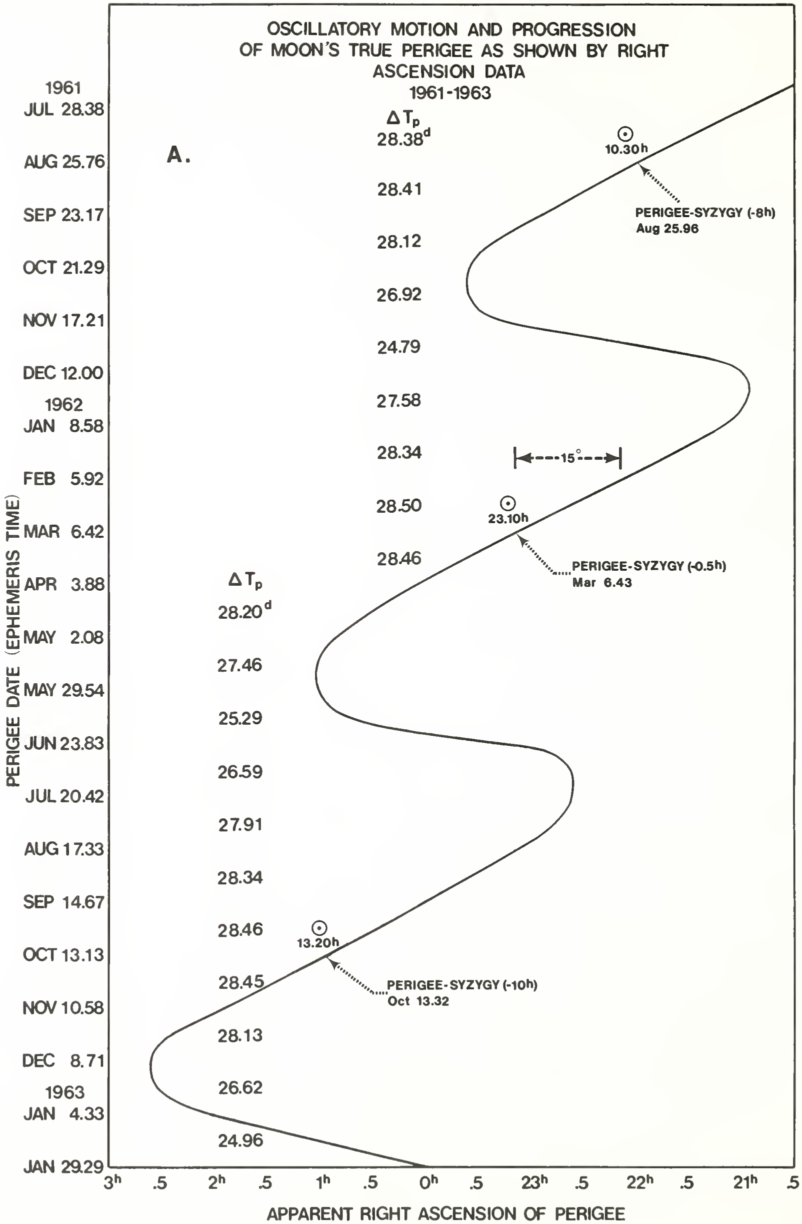


Figure 28A.—(Discussed in text.)

of data points available is not sufficiently large, nor closely enough spaced, to reveal the pattern of perigee movement over a few days at a time. Several different short-period and long-period motions of perigee must be separately distinguished:

a. Analytic computations made possible from the reduction formulae given in table 16B indicate a variable-speed, short-period retrograde motion of perigee on either side of, and including, the time of perigee-syzygy. This particular retrograde motion is the result of the perigee-syzygy alignment itself, and occurs only in those lunations containing such alignments.

b. The much larger and longer lasting *net* retrograde motion of perigee accompanying certain lunations in the aforementioned diagrams is caused by the perturbational action of the Sun when it is at or nearly at right angles to the line of apsides, with the only opportunity for the Moon to pass through perigee being at quadrature. (See the further clarification under "a" in the explanatory notes in connection with figs. 28B, C, below.)

c. Finally, the year-by-year net forward motion of perigee—resulting from an excess of direct motion in the alternating forward and retrograde movements of perigee in those months containing situations of close perigee-syzygy or perigee-quadrature, respectively—is exemplified by the continuing progression of this lunar position toward greater right ascensions or celestial longitudes.

The situation depicted by these four diagrams accords with the general concept of the motion of perigee during successive orbital revolutions of the Moon. This concept is represented in classic reference sources ranging from Sir Isaac Newton's *Principia,* 1686 (proposition LXVI, theorem XXVI, corollary VII, and subsequent manuscripts in the Portsmouth Collection) through Roger Long's *Astronomy* in five volumes, 1764 (book 4, chap. 4, pp. 624–625) down to Forest Ray Moulton's *Celestial Mechanics.* 2d rev. ed., 1914 (pp. 352–356).

More recent and comprehensive mathematical developments of lunar theory have been made by George W. Hill and Ernest W. Brown (see Reference Sources and notes, pt. II, ch. 3), together with the publication of the *Improved Lunar Ephemeris,* 1952–59 (1954) by the U.S. Naval Observatory. These advances—plus the innovation of the high-speed electronic computer—have made possible modern analyses such as those represented by the algorithmic expressions contained in the supplement to table 16 (table 16B—Refined Reduction Formulae, para. 3). The retrograde motion of perigee bracketing the time of perigee-syzygy alignment is described in the immediately following section.

3. The Special Motion of Perigee Close to the Position of Perigee-Syzygy Alignment

The Sun's apparent annual motion brings it recurrently to the same celestial longitude as the line of apsides of the lunar orbit, and at varying phases of the Moon. The result is an induced perturbation and angular displacement of the position of perigee. Since this perturbation is sometimes in a direct sense of rotation and sometimes in a retrograde sense, but with the greatest percentage of motion being in the forward direction, the net, long-term effect is the *mean progression of perigee* around the lunar orbit in a period of 8.849 tropical years. The average motion of perigee is thus $+0.111404°$/day or approximately $+3.043742°$/month. This perturbational angular velocity is a mean value based on the composite forces produced at all possible positions, configurations, and alignments of the Moon and Sun.

However, the perturbations of perigee are distinctively affected by the alignment of the Sun, Earth, and Moon at perigee-syzygy as the Moon moves to a position near the line of apsides at the same time the Sun is along this line. The orbital velocity of the Moon always exceeds the apparent velocity resulting from the annual motion of the Sun as well as that of perigee in any phase of its oscillatory motion. It is, therefore, the motion of the Moon bringing this body, upon occasion, nearly simultaneously to the position of perigee and into a syzygy configuration with the Earth and Sun which permits relatively short-period recurrences of perigee-syzygy alignment. This coincidence of events is responsible both for the phenomenon of perigee-syzygy and the associated special perturbations of the lunar orbit.

The increases in the eccentricity and semimajor axis of the Moon's orbit due to perturbations by the Sun at the time of perigee-syzygy have been discussed previously. The value of e can then increase by a maximum of 0.023 to a value 40 percent above its mean value (0.05490). Conversely, if the Moon reaches perigee [b] while in a position of quadrature with the Sun, the value of e is minimized (i.e., if the Sun is at a position along the extended

[b] It is noteworthy that although there are two orthogonal configurations involving perigee and either of the quarter phases of the Moon which are possible at the time of quadrature, only one of these represents true perigee-quadrature. The first (and true situation) is the actual arrival of the Moon at perigee while in either of its quarter phases, the Sun then being at right angles to the line of apsides. The alternate, spurious relationship is the arrival of the Sun at the longitude of the Moon's perigee position in orbit, with the first- or third-quarter moon located at right angles to the line of apsides. It is the astronomically defined case, with the Moon physically occupying the position of perigee, which is considered here and is depicted in the top portion of fig. 28B.

minor axis of the Moon's orbit while the Moon is at perigee, the smallest possible eccentricity of the lunar orbit results).

The motion of perigee is also affected in varying degrees by solar perturbations. These perturbations are a function of the phase angle between Earth, Moon, and Sun, and the closeness of alignment between the line of syzygies and the line of apsides in the lunar orbit.

The general expression for the angular rate of motion of perigee at any relative longitude with respect to the Sun and at any elongation of the Moon from the Sun is, very approximately:

$$\begin{aligned}\dot{\varpi} = &+0.11^\circ/^d \\ &-3.05^\circ/^d \cos(\ell - 2D) \\ &+0.96^\circ/^d \cos(\ell + 2D) \\ &+0.82^\circ/^d \cos(2\ell - 4D) \\ &-0.66^\circ/^d \cos \ell \ldots\end{aligned}$$

(many higher-order terms have been neglected; note that this motion is projected along the ecliptic rather than in the Moon's orbit plane)

where

$\dot{\varpi}$ = the angular rate of motion of perigee, in longitude, in degrees per day (a minus sign indicates retrograde motion, and a plus sign, direct motion)

ℓ = the angular distance, in longitude, of the Moon from perigee. (Note: This value is equivalent to the "average" mean anomaly L used in the computer printout of table 16—see the introduction to table 16.)

D = the lunar elongation, or angular separation of the Moon from the Sun, in longitude

With the Moon at perigee, $\ell = 0^\circ$, and this equation reduces to:

$$\begin{aligned}\dot{\varpi} = &-0.55^\circ/^d - 2.07^\circ/^d \cos 2D \\ &+1.26^\circ/^d \cos 4D - 0.26^\circ/^d \cos 6D \ldots\end{aligned}$$

At perigee-syzygy, the corresponding value for the rate of motion of perigee becomes approximately:

At either new moon ($\ell = 0^\circ$, $D = 0^\circ$) or full moon ($\ell = 0^\circ$, $D = 180^\circ$), $\dot{\varpi} = -1.6^\circ/^d$. And (with $\ell = 0^\circ$, $D = 90^\circ$) for perigee at first or third quarter, $\dot{\varpi} = +3.0^\circ/^d$.

Hence, with the Sun at right angles to the line of apsides, and the Moon at perigee and either first or third quarter (see fig. 28B), the motion of perigee is direct, with an angular velocity of approximately $+3.0^\circ/^d$. In a situation possible only in a different lunation, as the Moon approaches perigee-syzygy at either new or full phase, an induced small retrograde motion increases steadily in magnitude, reaching a maximum velocity of $-1.6^\circ/^d$ at the time of perigee-syzygy. (See also par. 1 under "Tidal Force Evaluating . . ." in ch. 5.) Thereafter, the direction of motion remains retrograde, but the negative angular velocity diminishes toward zero and then turns positive. At apogee-syzygy, $\dot{\varpi} = +3.3^\circ/^d$, approximately.

The net result of this retrograde motion of perigee in the vicinity of perigee-syzygy is to prolong slightly the period of time in which perigee and syzygy are close to each other. Thus, immediately prior to a perigee-syzygy alignment, with the motion of the Moon and perigee being in opposite directions and their *relative* (head-on) velocities increased to a maximum, a tendency exists to hasten the time at which the Moon reaches the position of perigee-syzygy. Subsequent to the perigee-syzygy alignment, with the motion of perigee in the same retrograde direction as before, but diminishing in velocity, the effect is to keep the position of perigee in the vicinity of syzygy for a slightly longer period.

The greater duration of time in which perigee remains in the vicinity of syzygy, together with the dual reinforcement of gravitational forces resulting from this near-alignment, yields a correspondingly increased tide-raising potential. This phenomenon will be discussed further in chapter 6 along with other factors producing an extension of the interval during which enhanced gravitational forces act at the time of perigee-syzygy.

* * * * *

Explanation of the Short-Period Motions of Perigee

In figure 28B, the positions of an hypothetically unperturbed lunar orbit and that of the actual perturbed orbit are shown. The latter orbit is a function (among other factors) of the changing value of e produced by the gravitational attraction of the Sun.

As has been shown earlier in this chapter, the perigee distance (q) of the Moon from the Earth is given by:

$$q = a(1 - e)$$

where a and e represent the semimajor axis and eccentricity of the lunar orbit, respectively.

a. It also has been noted previously that, at the time of perigee-quadrature, both the eccentricity and semimajor axis of the lunar orbit decrease (the former relatively faster than the latter), the value of the perigee distance increases, the curvature of this part of the lunar orbit becomes less, and the perturbed orbit lies outside the unperturbed orbit.

This situation is illustrated in the top portion of figure 28B. (For comparison, the phenomena of perigee-quadrature and perigee-syzygy have been plotted simultaneously on the same diagram, and the primed symbols corresponding to the position of perigee-syzygy alignment should, for the moment, be completely disregarded. These two phenomena do not, of course, occur together in any single lunation.)

In the present analysis, the position M_7 corresponds to the position of the Moon at a time approximately 7 days prior to the alignment of the Moon with the Sun at conjunction. The assumption is here made that no perturbing effects on the lunar orbit due to the Sun are present. The position P_7 similarly indicates the original position of perigee toward which the Moon is moving in this undisturbed orbit.

However, subject to the action of solar perturbations, the value of q increases and the perturbed orbit results. To con-

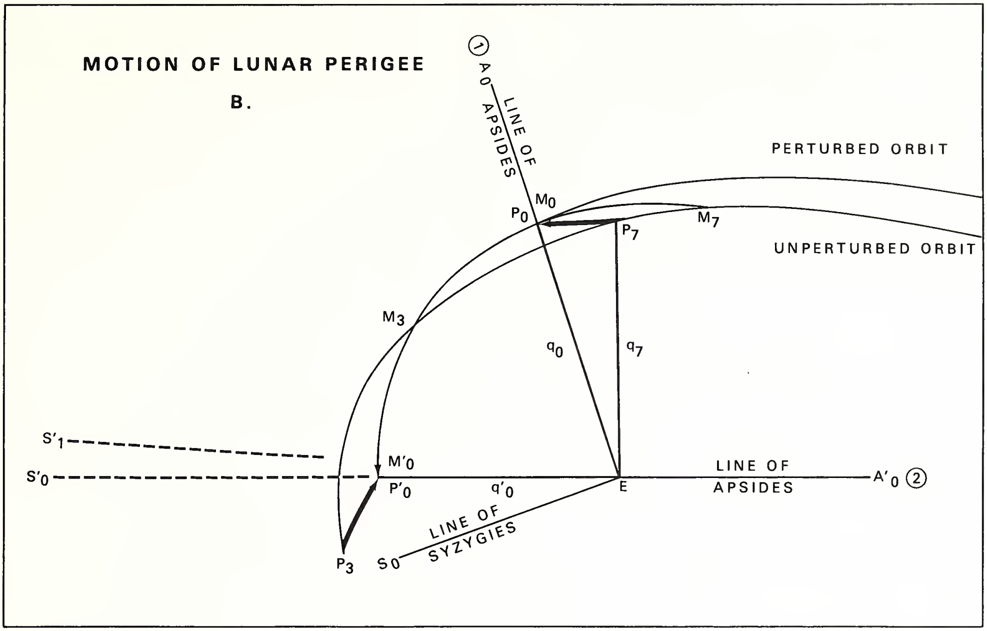


FIGURE 28B.—The positions of perigee-syzygy ($P'_0M'_0$) and perigee-quadrature (P_0M_0) are plotted on the same diagram to show the opposite motions of perigee—retrograde at perigee-syzygy and direct at perigee-quadrature. The location of the perturbed orbit outside the unperturbed orbit at quadrature, inside it at conjunction also is indicated. See the text discussion under "Explanation of the Short-Period Motions of Perigee."

form with this change in the distance of the Moon, beyond the position M_7 the path of the Moon swings outward from the Earth, producing the new orbital arc M_7P_0. Matching the Moon's motion in the same period of time, the position of perigee moves outward to establish an increased perigee distance q_0 at position P_0, very close to M_0. It is readily apparent from the diagram that the arc distance M_7M_0 is longer than the original span of the Moon's motion M_7P_7 necessary to reach perigee.

The net effect is to displace the original perigee position P_7 along the arc P_7P_0, which possesses a continuously increasing radius with respect to the Earth. This displacement is evidenced as a direct motion of the lunar perigee. The amount of the forward movement is a maximum in this case near perigee-quadrature.

This motion represents a short-period displacement of perigee during only a portion of one lunation. As such, it provides only a partial contribution to the *average* perigee motion over the entire lunation and throughout successive lunations. These short-period motions of perigee near perigee-quadrature and perigee-syzygy are, as a seeming paradox, exactly opposite to the average perigee-to-perigee motions shown in figures 30 and 32. It must be remembered, however, that the angular velocity of the Moon is the greatest during the perigee portion of its orbit, and it covers this portion of the orbit in the least number of days. Hence, the cumulative effect of the motion of perigee in that half of the orbit containing perigee is the least and is overshadowed by the cumulative effect of perigee motion during the Moon's passage through the opposite half of its orbit, completed over a greater number of days.

b. It has further been demonstrated previously that, at the time of perigee-syzygy, the value of e increases in the lunar orbit due to the effect of solar perturbations, and at a faster rate than a increases. A retrograde velocity of perigee becomes quantitatively significant at M_3, some few days prior to lunar conjunction with the Sun, and reaches its maximum value when the perigee-syzygy alignment (M_0') is reached. In this approach interval, the value of q continuously decreases (i.e., the lunar parallax becomes steadily greater).

In figure 28C, the path of the Moon close to the time of perigee-syzygy has been enlarged from figure 28B in order better to show the relationships between the perturbed and unperturbed orbits of the Moon. In this figure, the position P_3 represents the original position of perigee toward which the Moon is moving in its undisturbed orbit, from its initial position M_3. The distance q_0' represents the corre-

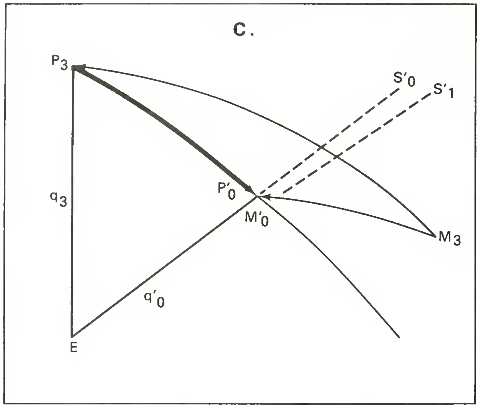


FIGURE 28C.—Enlargement of the left portion of figure 28B, defining the retrograde motion of perigee at the time of perigee-syzygy.

sponding perigee distance of the Moon from the Earth in this undisturbed orbit. In a period of 1 day the Sun, in its apparent annual motion eastward in the sky, has moved from S_1' to S_0'.

As the Moon also moves eastward toward the position of perigee-syzygy alignment ($M_0'S_0'$ or P_0'), the Sun's perturbational influence due to this alignment acts to increase the eccentricity of the lunar orbit, correspondingly reducing the value of q. The path of the Moon beyond M_3 in turn swings nearer to the Earth to accommodate this reduction in the perigee distance, thus producing the new orbital arc M_3M_0'. It is obvious that the arc M_3M_0' necessary for the Moon to reach the new position of minimum distance (q_0') from the Earth is shorter than the original arc M_3P_3.

The physical result is to displace the original perigee position P_3 along the arc P_3P_0' possessing a continuously shortening radius with respect to the Earth. This displacement action is evidenced as a retrograde motion of the lunar perigee. The amount of the retrograde displacement becomes greater, the greater is the reduction of q (i.e., the closer the position of perigee is to alignment with syzygy). The maximum retrograde motion therefore occurs at the time of perigee-syzygy. After the Moon passes through this position (P_0'), the retrograde motion of perigee decreases again.

* * * * *

4. Comparison of True and Mean Motions

Another way of representing the difference between the mean and true motions of perigee is by means of a graphic comparison of the relative motions of the Sun and Moon, plotted in the true and mean systems of reckoning. These comparative motions are illustrated in figures 29–30 and 31–32. In these diagrams, the angular position of the lunar line of apsides corresponding to a very close alignment of perigee-syzygy (1962 Mar. 6.5), as well as the positions of the Sun during the course of this same year, are indicated as the Sun apparently revolves around the Earth in consequence of the Earth's actual annual revolution around the Sun.

The family of concentric ellipses shown represents the successive monthly cycles of revolution of the Moon. Double-shafted arrows indicate the corresponding monthly motions of perigee. Figures 29 and 31 portray the mean motions of perigee, as they are assumed, for convenience in computation, in tidal theory. Figures 30 and 32 represent the *true* motions of perigee. As noted earlier, successive lunar orbitings are in no sense re-entrant ones, but continuously fail to close on the same position as the result of perturbations encountered in any one revolution. Accordingly—without loss in factual integrity—the Moon may, for greater ease in graphic presentation, be depicted as revolving, month by month, in the separate orbits indicated. These are drawn to successively smaller sizes to prevent overlapping and confusing crossovers between the adjoining elliptical paths.

According to the assumption of a perturbationally induced, but constant, mean daily motion, the Moon's perigee is conceived to move in a counterclockwise direction in the orbital plane, with the previously stated mean angular velocity of $+0.111404°/^d$. The rather sizable differences between this value, adopted for computational convenience, and the constantly changing lunar velocity which actually prevails is revealed by a comparison of figures 29 and 31 with figures 30 and 32.

When the true motion of perigee is plotted, over successive months, from the same data used to construct figures 30 and 32, the considerable differences between the true and mean motions is evident. The maximum true motion in orbit may be determined by taking the total angular distance through which the Moon revolves in orbit during an anomalistic month (a time period which is itself subject to a considerable variation in length—see table 17), and dividing this angle by the exact period between consecutive perigee-syzygies. By this means, the *true* average angular velocity of perigee in an anomalistic month containing a close perigee-syzygy alignment is found to be some $0.55°/^d$, or approximately five times that assumed for its *mean motion* during this same interval.

Selecting, as a starting point, and representative example, a date when the position of the Sun first comes within less than 30° of alignment of the line of apsides of the lunar orbit (on 1962 Jan. 8.5, in figure 30), the

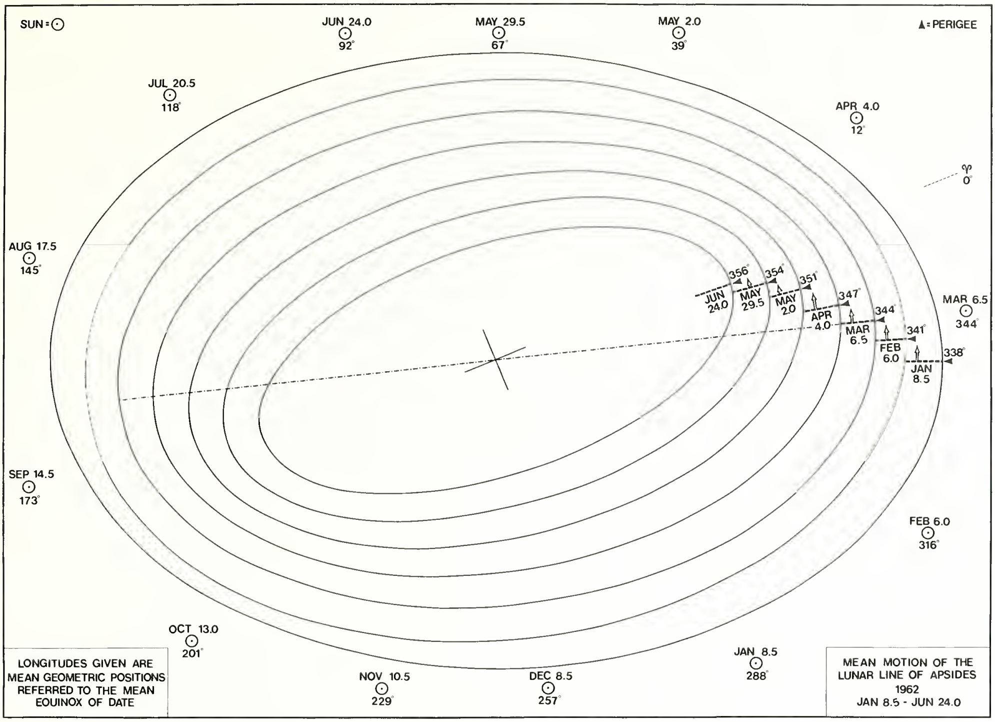


FIGURE 29.—(Discussed in text.)

subsequent motion of lunar perigee can be closely observed. As the longitude of the Sun comes increasingly closer to that of the perigee position during the immediately following months, it is obvious that a marked acceleration occurs in the true motion of perigee. (The perigee attains an average angular velocity of some 16° in 28.5 days, or $0.56°/^{d}$ between the perigee-syzygy alignments of Jan. 8.5 and Feb. 6.0 depicted in figure 30.)

This forward motion of the line of apsides (and with it the Moon's perigee position) continues for several successive anomalistic months (at an average angular velocity of between $0.54°/^{d}$ and $0.56°/^{d}$ in the example shown). The largest forward angular motions of perigee are generally centered around that perigee-syzygy date (of several always occurring in a row) when the separation-time between perigee and syzygy is the least of the series. Such maximum values in the forward angular motion of perigee usually do not occur during more than three successive months (or, at the absolute maximum, during four successive months) in any one perigee-syzygy cycle.

Following upon these maxima in perigee motion, the separation-time between perigee and syzygy becomes larger, and the forward motion of perigee diminishes. Some 4½ to 5 months after the first considerable forward motion of perigee began, this motion reduces to 0°, and thereafter reverses in direction.

Thereafter, the motion of perigee continues in a retrograde direction, and again this motion accelerates (in the period of regression illustrated in fig. 32, for example, to an average angular velocity of $0.98°/^{d}$). The retrograde motion is maximum at the time the Sun lies approximately at a right angle to the line of apsides. The motion diminishes rapidly as the longitude angle between the Sun and perigee further increases. (The latter angle is nearly that which, in the plane of the lunar orbit, separates the Moon

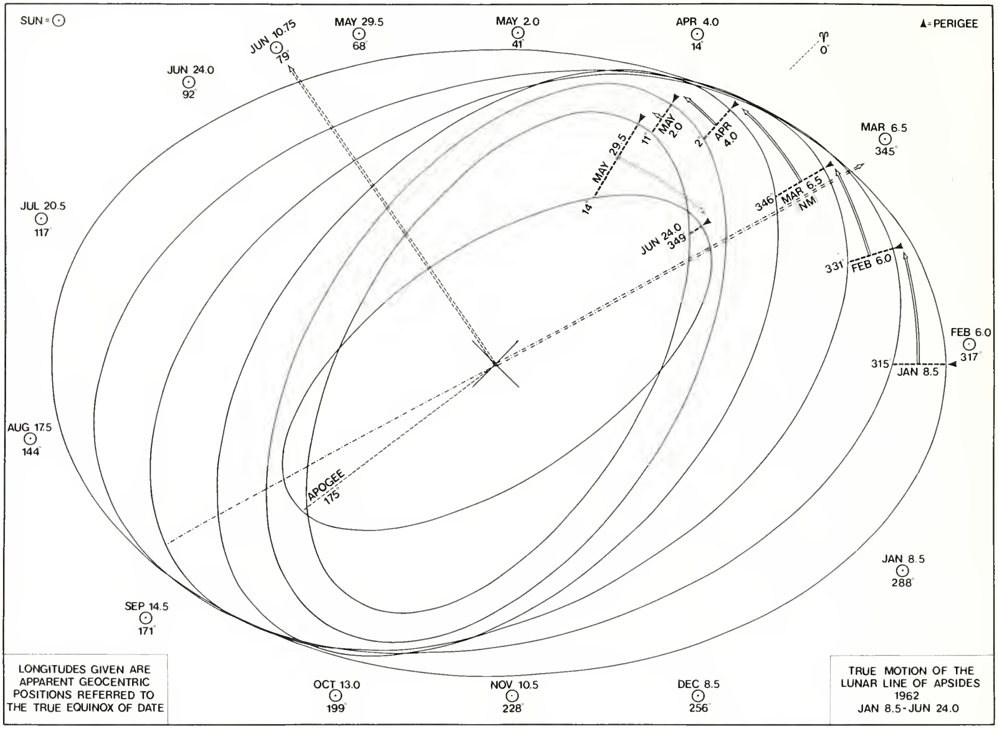


FIGURE 30.—(Discussed in text.)

from perigee and is known as the *true anomaly.*) By contrast with the direct motion of the line of apsides, the retrograde motion usually lasts for only two or, at most, three months between the two forward-moving cycles of perigee which normally occur in any one calendar year.

Since the forward (counterclockwise) motion of perigee takes place during approximately 4½ months of each year, while the retrograde motion generally occupies only 2–3 months, the net result is an average, cumulative forward motion of the axis connecting perigee and apogee which is known as the *progression of the lunar apsides.*

Both the averaged, long-range, forward motion of perigee and the intermittent retrograde movement may be further graphically illustrated by preparing, for the same close perigee-syzygy situation in each case, a comparative plot of the true and mean motions of perigee with respect to the time, as shown in figure 33. This diagram represents, in a somewhat different form, the same astronomical event of this type depicted in figure 30, and which was associated with the great mid-Atlantic tidal flooding of 1962 March 6.5.

In this diagram, the *mean motion* of perigee is derivable from its successive positions in mean longitude along the straight line *a–z*. The corresponding *true motion* of perigee may be obtained by taking differences in true longitude from the curve *b–y*. Forward motion occurs from *b* to *n*, retrograde from *n* to *q*.

5. The Minor Sinusoidal Variation Between True and Mean Longitude

Finally, the effect of the previously discussed perturbations in causing a small but measurable difference between the mean and true longitudinal positions of the Moon is shown in figure 34. The diagram represents a period of approximately 2 lunar months.

It is immediately apparent that, in terms of the small incremental function in longitude it is necessary to apply

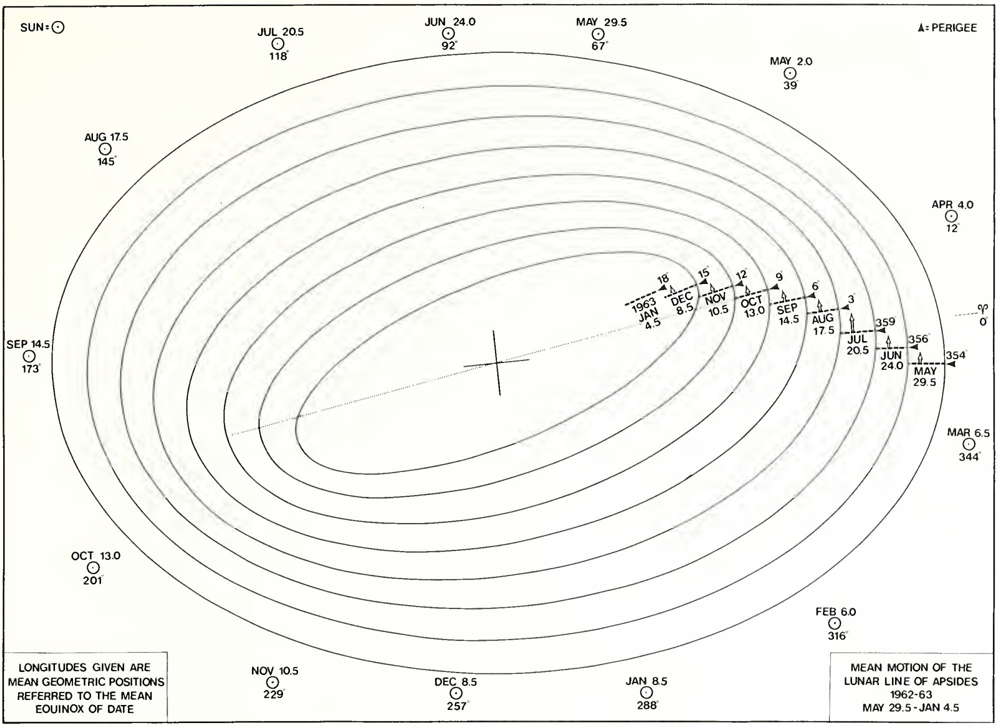


FIGURE 31.—(Discussed in text.)

in order to convert mean positions of the Moon to true positions, the correction becomes 0°0′ at times of both perigee and apogee. At these two positions in every lunation, the straight line representing mean longitudes of the Moon and the sinusoidal curve representing the deviation of positions in true longitude from those in mean longitude come together.

Hence, any variation in lunar gravitational force or in tide-raising potential resulting from the difference in position of the Moon in these individual coordinate systems is of no consequence at either of these two lunar apse positions, or at times of perigee-syzygy.

Paradoxically, the effect is exactly the opposite to that encountered under the analogous requirement for applying corrections to mean parallax to achieve true parallax. In this previously discussed case, the differences between true and mean parallax were found to reach a *maximum* at times of perigee-syzygy.

Subordinate and Counterproductive Effects on Perigean Spring Tides

Certain ancillary tidal influences are in no way assignable as direct causal factors in the production of perigean spring tides. However, because of their general dynamic influence upon all types of tides, they may play a significant role in either increasing or decreasing the amplitude of perigean spring tides after these have been generated by their own causal factors. Other actions present among the broad range of gravitational forces may be definitely counterproductive in connection with perigee springs, or any other tides. In this concept of providing a potential modification of existing forces and actions, these secondary influences will be included here.

Other important astronomical, oceanographic, and hydrographic factors contributing to the maximization of perigean spring tides will be discussed in the next chapter,

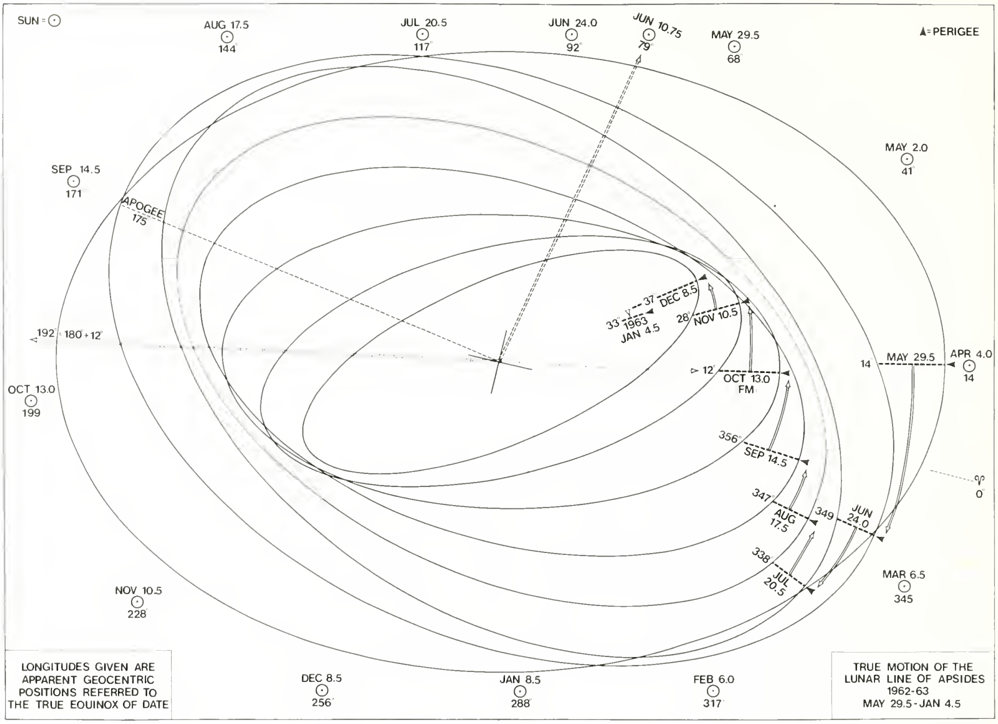


FIGURE 32.—(Discussed in text.)

and both the additive and partial amplitude-negating effects of wind and atmospheric pressure will be covered in chapter 7.

Effects of Declination on the Tide-Raising Forces

In figure 35, a tidal force reference system is defined by the rectangular coordinate axes *x*, *y*, and *z*. In this reference system, the *xz* plane represents that of the Moon's orbit and *xy* (the plane of the paper) a plane at right angles thereto, containing the zenith of the observing station *S*, located on the surface of the Earth. The angle θ in the *xy* plane represents the angular distance of the zenith above the Moon's orbital plane, and therefore is also equal to the zenith distance of the Moon. The declination of the Moon is given by $\delta_{☾}$, so that the geographic latitude of the observation station, $\phi = \theta + \delta_{☾}$. The distance of the place of observation from the center of the Earth is designated by ρ.

In the plane of the paper (i.e., with the Moon on the local meridian of the place), the total gravitational force of the Moon at *S* is indicated by the force vector **F**, which is resolvable into two components **X**, parallel to *x*, and **Y**, parallel to *y*. The angle *H* represents the angular altitude of the Moon above the horizon. *D* is the distance of the observing position from the center of the Moon, and *R* is the distance between the center of the Earth, *O*, and the center of the Moon, *C*.

The respective tide-raising components of force in terms of **X**, **Y** and **Z** are:

$$\mathbf{X} = \frac{2x}{R^3}; \qquad \mathbf{Y} = \frac{-y}{R^3}; \qquad \mathbf{Z} = \frac{-z}{R^3}.$$

Since the gravitational force potential is related to each of these components by the relationships

$$\mathbf{X}=\frac{\partial U}{\partial x}; \qquad \mathbf{Y}=\frac{\partial U}{\partial y}; \qquad \mathbf{Z}=\frac{\partial U}{\partial z},$$

the value of this potential can be derived by integration as follows:

$$U=\frac{\partial U}{\partial x}+\frac{\partial U}{\partial y}+\frac{\partial U}{\partial z}$$

$$=\frac{1}{R^3}\int 2x\,dx-\frac{1}{R^3}\int y\,dy-\frac{1}{R^3}\int z\,dz$$

$$=\frac{1}{2R^3}\,(2x^2-y^2-z^2)$$

$$=\frac{1}{2R^3}\,[2x^2+x^2-(x^2+y^2+z^2)].$$

Or, since $\rho^2=x^2+y^2+z^2$,

$$U=\frac{1}{2R^3}\,(3x^2-\rho^2).$$

Since $x=\rho\cos\theta$, $x^2=\rho^2\cos^2\theta$; $3x^2=3\rho^2\cos^2\theta$;

$$3x^2-\rho^2=3\rho^2\cos^2\theta-\rho^2=\rho^2(3\cos^2\theta-1)$$

$$\therefore U=\frac{\rho^2(3\cos^2\theta-1)}{2R^3}.$$

Introducing appropriate coefficients representing the effects of the relative masses of the Moon and Earth on the gravitational force potential U responsible for the tides, where:

g=the acceleration of gravity[c]
$m_{☾}$=the mass of the Moon
$M_{\oplus}$=the mass of the Earth
ρ=the radius of the Earth, assumed to be a true sphere
ρ_s=the mean radius of the Earth, regarded as a standard spheroid of revolution, with mass $M_{\oplus}$

Then:

$$U=g\left(\frac{m_{☾}}{M_{\oplus}}\right)\left(\frac{\rho_s}{R}\right)^3\frac{\rho^2}{2\rho_s}\,(3\cos^2\theta-1)$$

[c] According to the usual convention, the term *gravity,* here denoted symbolically by *g,* implies a modification of the universal force of *gravitation* to include certain other dynamic effects which are active beneath, on, or above the Earth's surface. The central force of gravitational attraction due to the mass of the Earth is reduced both by centrifugal force associated with the rotating Earth and by varying distance from the source of attraction resulting from a flattening in the Earth's figure toward the poles. The term gravitation is reserved for the general gravitational field in outer space, exclusive of these terrestrial effects. The universal or *Gaussian constant of gravitation,* denoted by *k,* is used in some equations involving the comparative ratios of the gravitational forces of extraterrestrial bodies (e.g., the Moon and Sun). It may be noted parenthetically that the symbol *g* also has been used on occasion in the text to indicate mean anomaly, a standard, although less frequent usage.

Since, for the present purpose, it may be assumed that $\rho=\rho_s$:

$$U=g\left(\frac{m_{☾}}{M_{\oplus}}\right)\left(\frac{\rho_s}{R}\right)^3\frac{\rho_s}{2}\,(3\cos^2\theta-1)$$

Further, in dealing with the height ΔS through which any unit mass m_1 of the equilibrium tidal waters will be raised by the potential energy against the gravitational acceleration g, $U=m_1 g\Delta S$ or, since m_1 equals unity,

$$\Delta S=\frac{U}{g}$$

$$\therefore \Delta S=\left(\frac{m_{☾}}{M_{\oplus}}\right)\left(\frac{\rho_s}{R}\right)^3\frac{\rho_s}{2}\,(3\cos^2\theta-1).$$

Developing this solution further by means of a standard astronomical triangle on the celestial sphere, the Moon is now represented as being at a point B, on the celestial equator, such that $\delta=0°$. The astronomical triangle is composed of the points P (the celestial pole), B (the position of the Moon), and Z (the zenith of the observer).

Employing the equation (pt. II, ch. 1) for conversion from the horizon system to the equatorial system of coordinates, and since θ is equivalent to the zenith distance, $\zeta_{☾}$:

$$\cos\theta=\cos\zeta_{☾}=\sin\delta_{☾}\sin\phi+\cos\delta_{☾}\cos h_{☾}\cos\phi$$

where $\zeta_{☾}$=the zenith distance of the Moon
=θ, the angular distance of the zenith above the plane of the Moon's orbit
$\delta_{☾}$=the lunar declination
$h_{☾}$=the hour angle of the Moon
ϕ=the geographic latitude of the observing position

Substituting the trigonometric portion of the tidal force potential, $(3\cos^2\theta-1)$ from its previous derivation, and letting $\zeta_{☾}=\theta$:

$$3\cos^2\theta-1=3\,[\sin\delta_{☾}\sin\phi+\cos\delta_{☾}\cos h_{☾}\,\phi]^2$$
$$=3\,[\sin^2\delta_{☾}\sin^2\phi+2(\sin\delta_{☾}\cos\delta_{☾}\sin\phi\cos\phi\cos h_{☾})+\cos^2\delta_{☾}\cos^2 h_{☾}\cos^2\phi]-1.$$

Since $\sin\delta_{☾}\cos\delta_{☾}=\frac{1}{2}\sin 2\delta_{☾}$

and $\sin\phi\cos\phi=\frac{1}{2}\sin 2\phi$,

$$\Delta S=\frac{\rho_s}{2}\left(\frac{m_{☾}}{M_{\oplus}}\right)\left(\frac{\rho_s}{R}\right)^3\left[3\sin^2\delta_{☾}\sin^2\phi+\frac{3}{2}(\sin 2\delta_{☾}\sin 2\phi\cos h_{☾})+3\cos^2\delta_{☾}\cos^2 h_{☾}\cos^2\phi\right]-1.$$

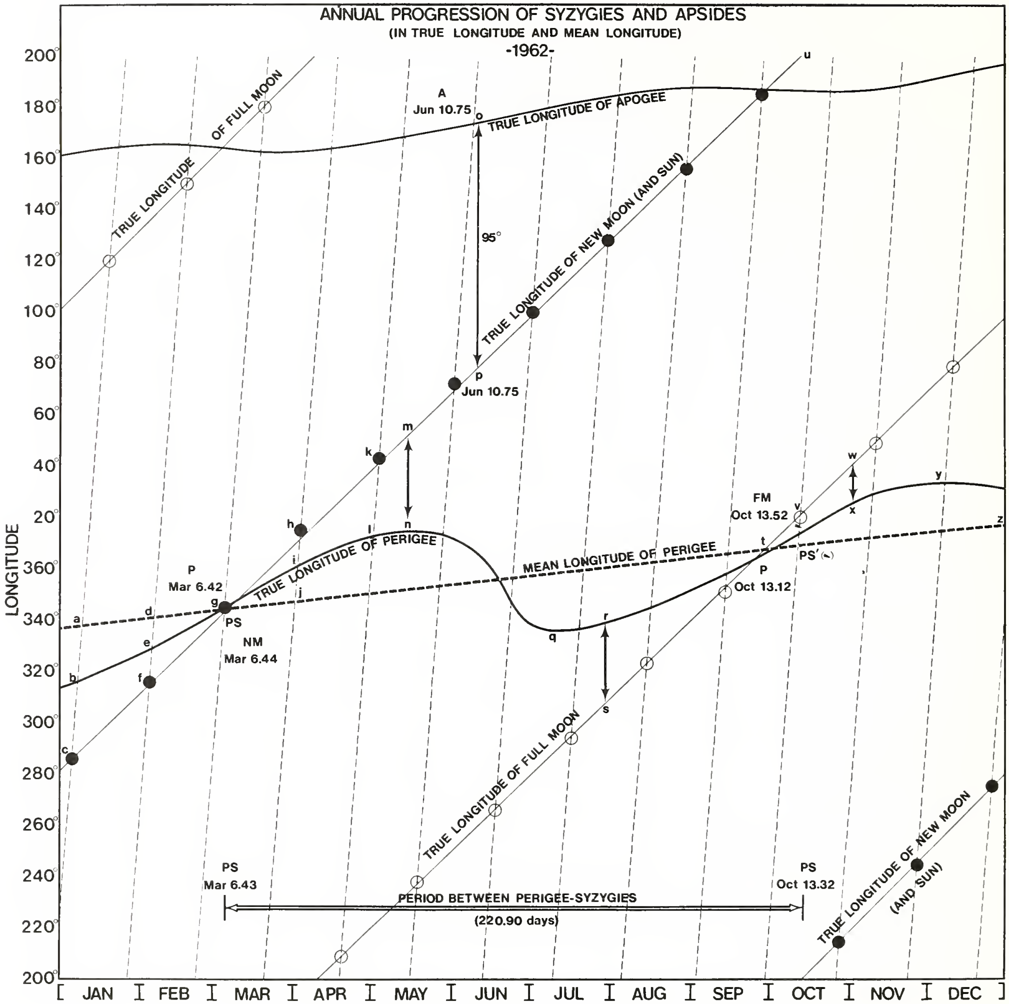


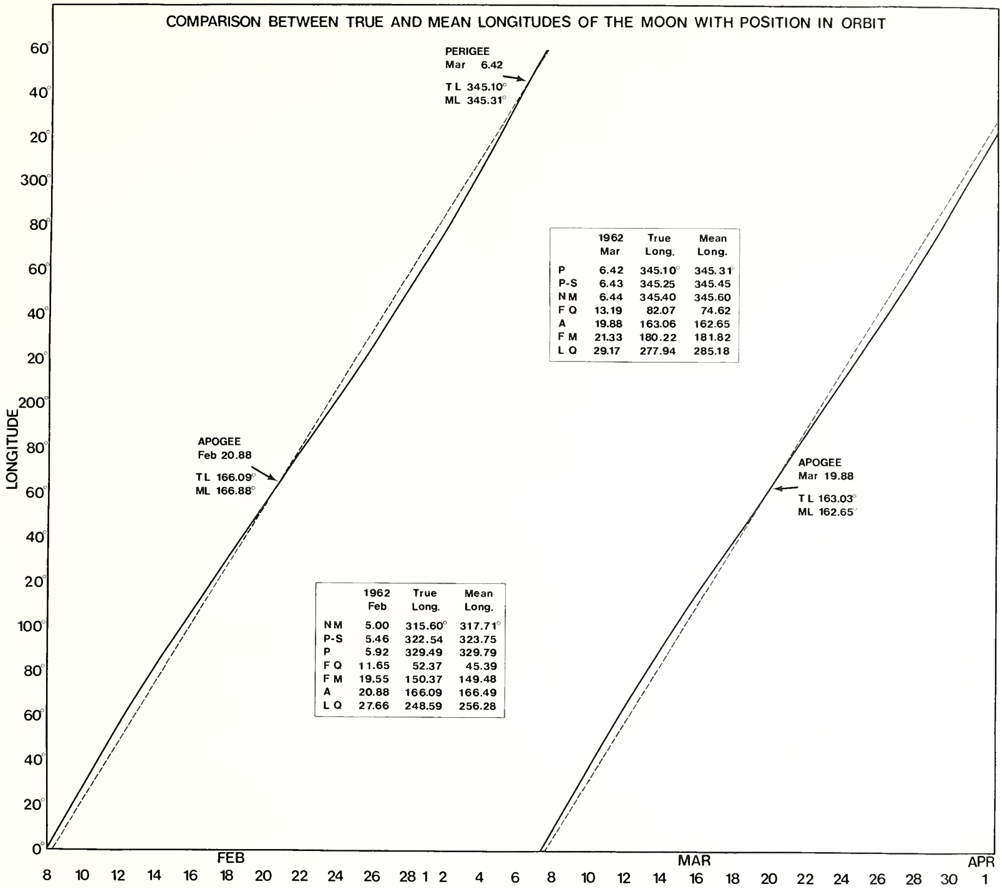
FIGURE 33.—(Discussed in text.)

For a location at the Equator, $\phi=0$, and in this position:

$$\Delta S=\frac{\rho_s}{2}\left(\frac{m_☾}{M_\oplus}\right)\left(\frac{\rho_s}{R}\right)^3[3\cos^2\delta_☾\cos^2 h_☾-1].$$

Similarly, when the Moon is on the meridian, $h_☾=0°$ which has a significance in tide-raising action described particularly in chapter 6. For $h_☾=0$:

$$\Delta S=\frac{\rho_s}{R}\left(\frac{m_☾}{M_\oplus}\right)\left(\frac{\rho_s}{R}\right)^3[3\cos^2\delta_☾-1]$$



	1962 Mar	True Long.	Mean Long.
P	6.42	345.10°	345.31°
P-S	6.43	345.25	345.45
N M	6.44	345.40	345.60
F Q	13.19	82.07	74.62
A	19.88	163.06	162.65
F M	21.33	180.22	181.82
L Q	29.17	277.94	285.18

	1962 Feb	True Long.	Mean Long.
N M	5.00	315.60°	317.71°
P-S	5.46	322.54	323.75
P	5.92	329.49	329.79
F Q	11.65	52.37	45.39
F M	19.55	150.37	149.48
A	20.88	166.09	166.49
L Q	27.66	248.59	256.28

FIGURE 34.—(Discussed in text.)

or the tidal height is a fixed function of the constants indicated, and varies directly only as $\cos^2 \delta_{☾}$.

Maximization of Declination in the 18.6-Year Period of the Lunar Nodical Cycle

Another tide-modifying factor which has a direct connection with the lunar declinational effects above described is the lunar nodical cycle. This involves a periodic revolution of the Moon's line of nodes in a westerly or retrograde direction around the lunar orbit. (The line of nodes is the axis joining the two points, 180° apart, at which the orbit of the Moon crosses the ecliptic.) The slow, retrograde motion of the nodes is the result of perturbations induced in the lunar orbit by the Sun's gravitational influence.

Since the Moon's orbit is inclined to the ecliptic by some 5°9′ (the actual value may range from 4°56′ to 5°20′ due to other perturbations), the Sun continuously strives to pull the plane of the Moon's orbit into its own plane, that of the ecliptic. However, in accordance with the laws of precessional motion in rotating bodies, instead of this action being completed, an alternate motion is introduced at right angles to the applied force. This

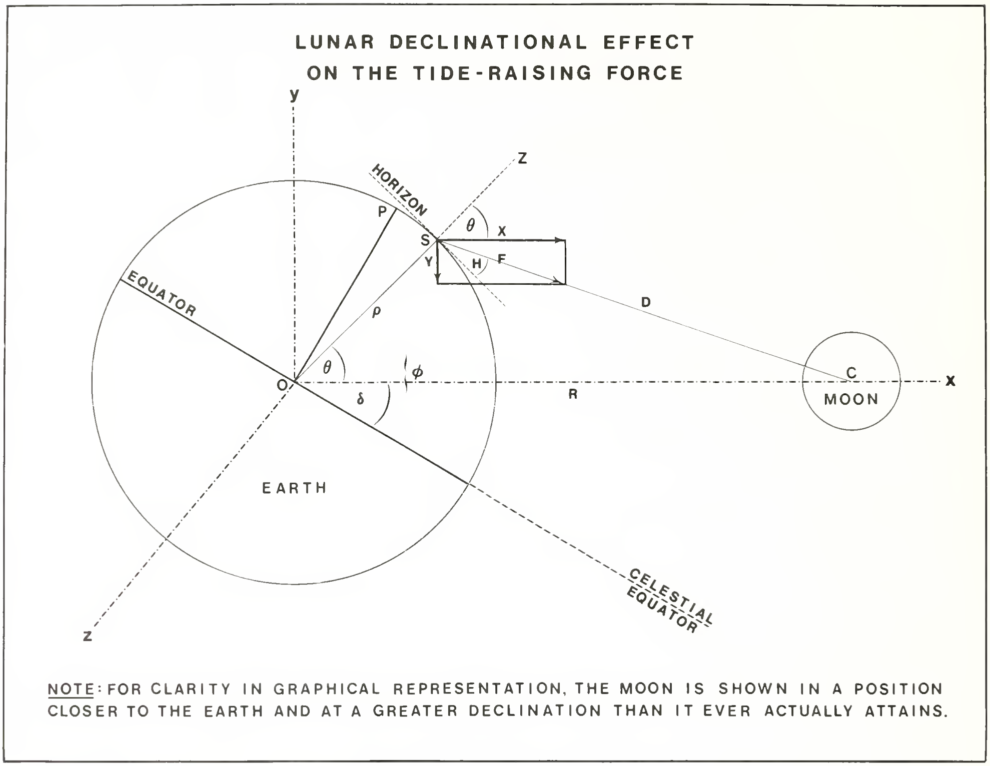


FIGURE 35.—(Discussed in text.)

results in a revolution of the pole of the Moon's orbit around the pole of the ecliptic.

At the same time, rather than any permanent change occurring in the inclination of the Moon's orbit, the nodes shift westward and complete one circuit of the lunar orbit in 18.6 years.

This regression of the nodes along the ecliptic gradually alters the maximum angle which the orbit of the Moon can make with the celestial equator. The *average* angle of inclination of the Moon's orbit with the ecliptic is the aforementioned 5°9′, and the average angle between the celestial equator and the ecliptic (termed the *obliquity of the ecliptic*) is 23°27′. Because of the geometric relationships involved (see fig. 36), the separation between the lunar orbit and the celestial equator may range, over one-half the nodical cycle, from the direct sum of these angles to the simple difference between them.

Thus, when the Moon's ascending node coincides with the vernal equinox, the maximum declination (either positive or negative) of the Moon is 23.5°+5°, or 28.5°. When the Moon's descending node coincides with the vernal equinox—and the ascending node coincides with the autumnal equinox—the value of the maximum declination is only 23.5°—5°, or 18.5°. The first condition results in a corresponding range of 57° in lunar meridian altitude; the second produces a range in meridian altitude of only about 37°.

The above-mentioned variations in lunar declination. involving a maximum semimonthly range of —28.5° to +28.5°, and a minimum semimonthly range of —18.5° to +18.5° occur, under the appropriate circumstances at times which are one-half of a nodical cycle, or 9.3 years apart. The effect of this variation in increasing or decreasing the Moon's orbital velocity at certain epochs in the nodical cycle is shown at the end of the present chapter (Case 2). This readily verifiable phenomenon leads quite naturally to another related aspect of the lunar declinational influence on the tides which is of direct importance to the present discussion.

Aside From a Lack of Onshore Winds, Why Does Coastal Flooding Not Occur With Every Perigean Spring Tide?

The principles of scientific method require the application of a series of negative as well as positive tests for the adequacy of any scientific hypothesis. Specifically, this necessitates the fulfillment of both the negative and positive premises in the classic set of syllogisms: "If p is true, q is true; if p is false, q is false," described as equivalent propositions in deductive logic.

As space permits, an effort will be made throughout this work to include such a positive-negative balance of supporting checks. (A meaningful example is the inclusion, in table 27, of a realistic sampling of cases of extremely high astronomical flooding potential, yet total absence of any tidal flooding, despite the extremely close perigee-syzygy alignments. These situations are clearly explainable, however, by means of the accompanying weather maps as lacking the necessary contribution of onshore winds.)

The first of two examples entails an equally accountable reduction in the flooding potential of perigean spring tides under certain conditions. The accompanying analysis also helps to answer the very cogent question "Why does tidal flooding not occur at every close alignment of perigee and syzygy?"

Each of the examples under discussion involves the apparent daily motion of the Moon on the celestial sphere. In both instances, actual daily changes in lunar right ascension have been obtained from *The American Ephemeris and Nautical Almanac* for the dates concerned. As an extension of the similar, although more general example in part II chapter 2, it is now possible to evaluate these two separate situations in which the combined effects of the Earth's diurnal rotation and the Moon's orbital motion are incorporated.

One definitely significant aspect shown by the results of the subsequent computations is the strong likelihood that a perigee-syzygy alignment occurring in the first of the two circumstances under consideration will have a relatively small tidal flooding potential. This is despite the simultaneous presence of other generally favorable tide-building forces and conditions.

The foregoing statement, it is emphasized, defines an event of lesser statistical probability, but does not imply total exclusion. This assertion should in no way be interpreted to mean that tidal flooding will *not* ensue when a situation of large lunar declination occurs at the same time as perigee-syzygy. An exception is particularly possible where the Sun is in an exactly opposite (or similar) declination and therefore in the same plane as the Moon, and the production of a large lunar parallax results from this circumstance (see table 13). Furthermore, conditions may exist where the additional tidal range induced by the phenomenon of diurnal inequality associated with a large lunar declination is locally important to the production of flooding. Finally, yet another exception to the previously stated example exists in the second case of the two which follow, illustrating the oppositely acting effects of an extreme lunar declination.

It is necessary, at this point, to distinguish between these two different circumstances which arise from the 18.6-year nodical cycle and which involve, respectively, the association of a perigee-syzygy situation with:

1. A path of extreme lunar declination, resulting in a corresponding very large inclination between the lunar orbit and the celestial equator—with the Moon being on or near the celestial equator at the time of perigee-syzygy.

2. A flattened peak of the declination curve, combined with an extreme maximum in lunar declination, thereby permitting a correspondingly large lunar motion in right ascension—the Moon being at this high declination at the time of perigee-syzygy.

These two cases will be discussed from their contrasting points of view, first in an analytic fashion, and then by the application of actual numerical data.

The first example selected for investigation occurred on 1950 April 2. In this case, the coincidence between the ascending node of the lunar orbit and the vernal equinox just prior thereto produced (1) an extreme declination of the Moon and, in consequence, (2) a maximum angle of inclination between the Moon's orbit and the celestial equator.

The situation presented is one in which, near the celestial equator, the component of declinational movement of the Moon (see analogous curves of figs. 44, 152) is very large, while the movement in right ascension *as a function of steep orbital inclination alone* is small. As noted earlier, unless this factor is offset by a large parallax (e.g., at perigee-syzygy) it tends to reduce the possibility for a protracted tidal day. The declinational motion of the Moon likewise remains large throughout most of the lunation, producing relatively sharp-pointed peaks at the two declination maxima. This results in comparatively short periods of time in which the corresponding motion of the Moon in right ascension remains at or near its own largest values (i.e., at the top of the crest and at the bottom of the trough of the curve, where the slope is zero, and where most of the Moon's motion is in right ascension).

Combined Effect of Changing Parallax and Large Declination on the Moon's Hourly Motion in Right Ascension

The major influence controlling the apparent hourly motion of the Moon in *celestial longitude*, $\Delta\lambda_{☾}$, is the Moon's instantaneous parallax, with but little contribution from celestial latitude because of its small value, even at maximum. By contrast, the Moon's motion in *right ascension*, $\Delta\alpha_{☾}$, is strongly affected by its corresponding position and motion in declination. Although the Moon's movement in right ascension, as in celestial longitude, is duly influenced by its variation in orbital velocity between perigee and apogee, this is by no means the sole contributing factor in its apparent daily and hourly motions.

There is no consistent, one-to-one correlation between the hourly motion of the Moon in right ascension and any single astronomical circumstance—because of the harmonic interrelationship between all parameters involved. However, the following general principles may be deduced covering the various major factors of influence. All deal specifically with the Moon's relative motions in right ascension and declination, as a cofunction of its instantaneous position in declination:

1. Exclusive of the effects of parallax, the two times at which the maximum hourly motions of the Moon in right ascension occur in any one month are usually less than a day from, but rarely exactly coincide with, the two times of maximum declination during this same lunation. (See also paragraph 3, below.) As the positions of the respective semimonthly peak and trough of the curve of $\delta_{☾}$ plotted against $\alpha_{☾}$ or time (fig. 44) are reached, and the value of the slope $\Delta\delta_{☾}/\Delta\alpha_{☾}$ becomes equal to zero, all of the Moon's motion occurs in α. Accordingly, the maximum value of $\Delta\alpha_{☾}$ also occurs very nearly at the time that $\Delta\delta_{☾}$ reaches its zero value. The value of $\Delta\alpha_{☾}$ is always positive, since the direction of the Moon's movement is continuously counterclockwise.

2. The two maximum values of $\Delta\alpha_{☾}$ which occur in each synodic month consist of a larger maximum and a smaller maximum. These may occur for either (+) or (−) values of $\delta_{☾}$ and without regard to the sign of $\Delta\delta_{☾}$. The two distinct maxima having different amplitudes are a function of the Moon's varying velocity in its elliptical orbit.

During the anomalistic month, the Moon moves the fastest in its orbit (and therefore in either celestial longitude or right ascension)—from the effect of parallax alone—in a period extending from approximately 5 days before perigee to 5 days after perigee. Conversely, the Moon's apparent motion from this cause alone is the slowest from about 5 days after perigee to 5 days before perigee (bracketing the apogean portion of the orbit). The relative angular velocity of the Moon is also a function of the comparatively greater proximity (or the greater distance) of the Moon from the Earth, subject to the dynamic conditions creating such extremes at times of proxigee-syzygy and exogee-syzygy—or establishing moderate parallax distances at times in between. The Moon moves considerably faster than usual and the value of $\Delta\alpha_{☾}$ increases when the parallax is large, and the Moon's motion is slower when the parallax is relatively small—even though the latter parallax value may represent a maximum for that particular lunation.

3. The largest value of $\Delta\alpha_{☾}$ does *not* necessarily occur coincidentally with the largest value of $\delta_{☾}$ during the year; neither must it occur simultaneously with the closest separation-time between perigee and syzygy in the year.

4. The maximum value of $\Delta\delta_{☾}$, on the other hand, usually occurs very close to, but not necessarily simultaneously with, the two times each month when the Moon crosses the celestial equator. This corresponds to the point of inflection in the curve of the Moon's motion in declination, when this is plotted against motion in right ascension. At such times, the maximum component of the Moon's total motion is in the coordinate of declination, and the least motion is in right ascension.

The combination of a small lunar motion in right ascension and a limited period of maximum tidal force application establishes a somewhat less favorable situation for either enhancing or prolonging the tidal forces present. Therefore, despite the fact that very large parallax values may occur at such times through the coincidence of a close perigee-syzygy alignment, the situation remains an essentially negative one for the maximum development of perigean spring tides, and offers an excellent opportunity for verification of the "If not p, then not q" aspect of the hypothesis being tested.

Effects of Extreme Lunar Declination on Motions in Right Ascension

A subsequent frequently discussed aspect of the Moon's apparent daily and hourly motions in right ascension relates to the catch-up motion of the rotating Earth upon these lunar motions in α variable with different times and circumstances. When the Moon is observed in a position close to the celestial equator, the factor of changing angle of inclination of the Moon's orbit with respect to the celestial equator becomes of considerable significance. As a seeming paradox, both at the minimum as well as the maximum lunar declinations, the conditions which determine the amount of motion of the Moon in right ascension are affected (but in an opposite manner) by the ultimate magnitude of the greatest northern and southern declinational excursions of the Moon. As will be shortly seen, the effect of observation of the Moon from the Earth's surface rather than from its center, to which all geocentric parallaxes are referred, is also an important factor in the present connection.

The increased steepening of the angle of inclination between the lunar orbit and the celestial equator at times of extreme lunar declination is demonstrated in the first of the following quantitative analyses. The especially notable increase in the angle between the Moon's orbit and the celestial equator is revealed as one proceeds toward the Earth's Equator. It is at this point that the angle of inclination reaches a maximum and reduces the length of the lunar day (the period of time between successive lunar transits of the meridian) to its extreme minimum value. This shortening of the available time during which the increased gravitational forces created by a perigee-syzygy alignment can act partially offsets the greater amplitudes and flooding potential of perigean spring tides when they are associated with such conditions.

As shown in figure 36, upon those occasions when the vernal equinox and the ascending node of the lunar orbit coincide, the geocentric angle of inclination (J_o) between the Moon's orbit and the celestial equator can attain its maximum value slightly in excess of 28.5°. However, the Moon's sizable parallax angle can add appreciably to this value as measured from the Earth's surface.

Woolard and Clemence [5] have given appropriate equations which permit a quantitative analysis of the differences caused by the parallax effect. If J represents this same angle of inclination, but as measured *topocentrically* from a point on the surface of the Earth, its value is defined by:

$$\tan (90° - J) = \frac{x' - \xi'}{y' - \eta'}$$

where

$$x' = (1/\pi)'' 15 \cos \delta_{☾} (\Delta\alpha_{☾})^s$$

$$y' = (1/\pi)'' (\Delta\delta_{☾})''$$

$$\xi' = \rho \cos \phi' \cos h_{☾} (dh/dt)$$

$$\eta' = \rho \cos \phi' \sin \delta_{☾} \sin h_{☾} (dh/dt).$$

Assuming the Moon to be subject to its various actual and apparent motions on the celestial sphere, and to be referenced both in a rectangular coordinate system, x and y, and in the equatorial coordinate system, α and δ, then:

x' and y' are the rates of change of the rectangular coordinates x and y (with origin at the center of the Earth).

$x = \rho \cos \alpha_{☾} \cos \delta_{☾}$; $y = \rho \sin \alpha_{☾} \cos \delta_{☾}$
ρ = the radius vector from the center of the Earth through the point of observation on the Earth's surface to the Moon

ξ' and η' are the rates of change of the coordinates of the observer on the surface of the Earth, along the radius vector from the Earth's center to the Moon (the motion being caused by the rotation of the Earth)

$\pi_{☾}$ = the geocentric horizontal parallax of the Moon
$\delta_{☾}$ = the apparent declination of the Moon
$\Delta\alpha_{☾}$ = the hourly change in geocentric right ascension of the Moon
$\Delta\delta_{☾}$ = the hourly change in geocentric declination of the Moon
$h_{☾}$ = the hour angle of the Moon, taken as positive in a westerly direction from the local meridian
dh/dt = rate of change of the Moon's hour angle with time, taken as positive west of the meridian, and negative east of the meridian
ϕ' = the geocentric latitude of the place of observation

As in the example of chapter 2, the Moon is assumed to be on the celestial equator, and to be transiting the meridian of the U.S. Naval Observatory in Washington, D.C.

$$\phi' = 38°55'14.0''$$

$$\rho \cos \phi' = 0.77906.$$

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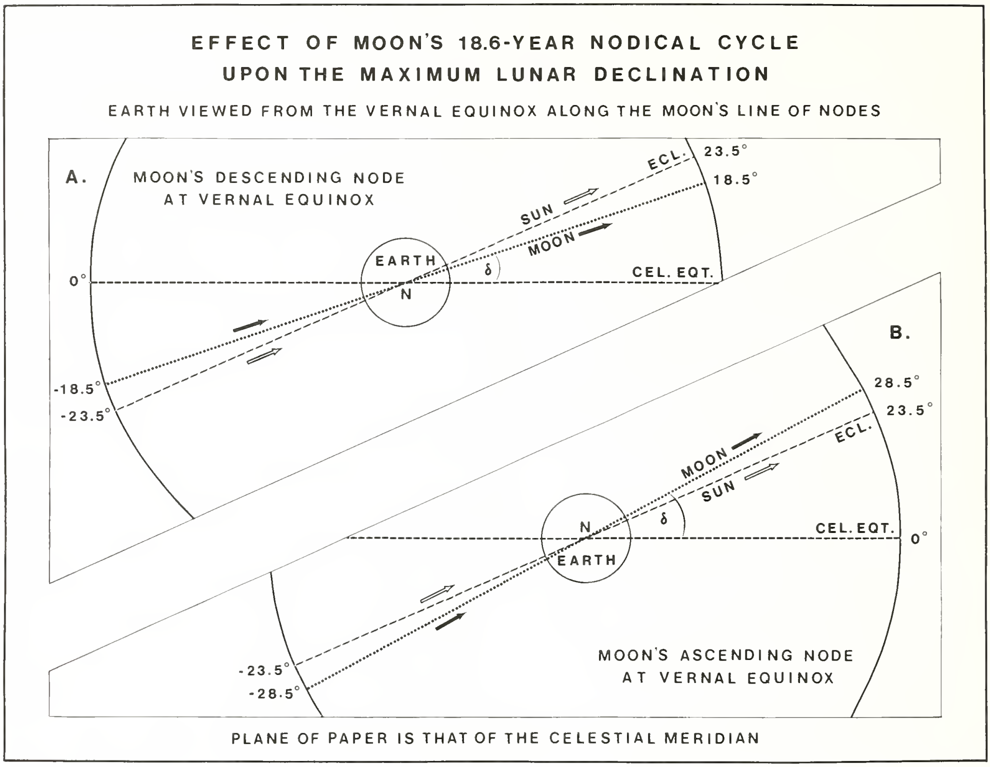

FIGURES 36A, B.—(Discussed in text.)

The Moon's parallax $\pi_☾$ is also assumed for convenience to be $60'(=3{,}600'')$.

In the year 1950, a very good example of the coincidence of the lunar ascending node and the position of the vernal equinox occurred.[6] (With ☊ at ♈, $\lambda_☊=0°$.) On September 19 at 0400 G.c.t., the Moon attained a maximum southerly declination of $-28°43'47.3''$ for this year. Approximately 6 months earlier, near 1200 G.c.t. on March 26, as the ascending node coincided with the *position* of the autumnal equinox ($\lambda=90°$) the Moon reached a maximum northerly declination of $+28°42'19.1''$ for the year. The values of the astronomical latitude around these same times were $\beta_☾=-5°16'55.9''$ on September 19.0, G.c.t., and $\beta_☾=+5°10'31.3''$ on March 26.0, G.c.t. A relatively high value of each semimonthly maximum in lunar declination persisted during every lunation throughout the year.

The probability that a simultaneous alignment between perigee and syzygy, as well as the lunar node, will occur at the exact time of either the vernal or autumnal equinox is, statistically, very remote. The period of revolution of the vernal equinox caused by the precession of the equinoxes is 25,800 years (one-half of this, or 12,900 years is, therefore, required for either of the two equinoxes to revolve to the position of the other). For all practical purposes in the present tidal discussion, the vernal equinox may be regarded as essentially stationary, and only the motion of the lunar node with respect to it in a mean revolutionary period of 6,798.4 days (18.6 years) need be considered.

A period of time equal approximately to the average of a synodic and an anomalistic month occurs between each instance in the customary *pairs* of perigee-syzygy alignments possessing a separation-interval (P−S) of +24 hours. (See table 16.) Following the smallest P−S value of any one close perigee-syzygy alignment, the mean interval to the next comparably close alignment will be either 191.95 days or 221.48 days, depending upon the controlling conditions enumerated in chapter 6, "Cycles of Alternation in Perigee-Syzygy Alignments."

The possibility of securing a coincidence between the combined condition of perigee-syzygy and both the lunar node and one of the equinoxes is made further remote by the fact that, as perigee and syzygy come into alignment, the position of perigee moves rapidly forward, subject to solar perturbations. The opportunity for arriving at even a near-commensurability between these four elements is thus even further reduced.

For the record only—recognizing that the periods covered by the tabulated data, and the data alone, do not cover all possible cases, with any rigorous interpretation thereof thus being rendered invalid—the following summation is made:

1. Only two among the 1,318 cases of perigee-syzygy *with a separation-time of 24 hours or less* occurring between 1600 and 1999 and listed in table 16, fall within even the same year as one of the 19 cases of extreme lunar declination listed in table 11, covering the 342-year period of the present study.

2. Among the 100 representative examples of major coastal flooding occurring at a time of perigee-syzygy, cataloged in table 1, only three cases occur even in the same year as that in which an extreme value of the lunar declination occurs. The three flooding cases involved (which are mutually inclusive of the two indicated in the first paragraph) are those of 1894 January 22 (perigee-syzygy separation-time, −24h), 1932 November 2 (−13h), and 1969 December 10–14 (+38h).

3. For several years in a row both before and after an extreme declination is attained, the lunar declination remains above-average in its monthly values throughout the entire year. However, the three cases mentioned of flooding which occurred in the same year as that of an extreme lunar declination were at least 8 months removed from the exact date of the extreme declination.

It is tacitly obvious that no solar or lunar eclipses can occur on these exact dates of highest possible lunar declination—but may occur on dates during the same year of high lunar declinations when the lunar node and the position of the Sun very nearly coincide. In the same manner, perigee-syzygy may occur on some other date of node-perigee-syzygy alignment throughout the year when the Moon may also be in a position of crossing the celestial equator. On the other hand, previously mentioned factors may apparently somewhat paradoxically *support* an increase in tidal flooding potential under certain conditions of high lunar declination, as will be brought out in subsequent chapters. It is because of the various commensurate possibilities that an examination of the differences between the two cases included in the following discussion is important.

TABLE 11.—*Approximate Dates on Which Maximum Lunar Declinations Occurred, According to the 6,798.4-Day Nodical Cycle*

(Based on Epoch 1932 January 12.1)

1634 Mar. 19.7	1820 May 7.7
1652 Oct. 29.1	1838 Dec. 18.1
1671 June 10.5	1857 July 29.5
1690 Jan. 19.9	1876 Mar. 9.9
1708 Sept. 1.3	1894 Oct. 20.3
1727 Apr. 13.7	1913 June 1.7
1745 Nov. 23.1	1932 Jan. 12.1
1764 July 4.5	1950 Aug. 23.0
1783 Feb. 13.9	1969 Apr. 3.4
1801 Sept. 26.3	(1987) Nov. 13.8

When the Moon crossed the celestial equator on April 2, during that particular cycle which contains the extreme maximum lunar declination, the relatively large hourly motion in declination necessary to accomplish this large excursion from the celestial equator was clearly evident. This position represented a point of inflection between the trough and peak of the curve, where the slope of the curve in the declination component reached a maximum.

The hourly differences in right ascension and declination of the Moon subject to this circumstance, occurring at approximately 0230 G.c.t. on April 2, were $\Delta\alpha_{☾}=130.97^s$ and $\Delta\delta_{☾}=-1{,}075.6''$. The latter value indicates the greatest hourly change in declination for the year. The corresponding hourly differences with the Moon on the celestial equator during the second cycle of maximum declination, at about 2130 G.c.t. on September 12, were $\Delta\alpha_{☾}=125.40^s$ and $\Delta\delta_{☾}=-1{,}030.8''$. (It should be pointed out that, for various reasons, the maximum value of $\Delta\delta_{☾}$ does not coincide precisely with the time at which the Moon crosses the Equator. In the first case, $\Delta\delta_{☾}$ reaches a greater value of $-1{,}078.6''$ at about 0930 G.c.t. on April 2, in the second case, $\Delta\delta_{☾}$ reaches a value of $-1{,}033.2''$ at about 0330 G.c.t. on September 13. The greatest value of $\Delta\alpha_{☾}$ more nearly—but again not exactly—agrees with the time the Moon reaches its extreme declination for the year.)

1. Decrease of Motion in Right Ascension, and Shortening of the Tidal Day at Times of High Lunar Inclination to the Celestial Equator

Selecting the April 2 example of the Moon's crossing of the celestial equator as representative of such a high-inclination situation, and using the appropriate value of the lunar parallax ($\pi_☾ = 60'25.88''$) at this time:

$$x' = 1/3626'' \times 15 \cos 0° \times 130.97^s$$
$$= 0.00028 \times 15 \times 1 \times 130.97 = 0.55007$$

$$y' = 1/3626'' \times 1075.6''$$
$$= 0.00028 \times 1075.6 = 0.30117$$
$$\xi' = 0.77906 \times \cos 0° \times 0.24956 \text{ radian}$$
$$= 0.19442$$
$$\eta' = 0.77906 \times \sin 0° \times \sin 0° \times 0.24956 \text{ radian}$$
$$= 0.77906 \times 0 \times 0 \times 0.24956 = 0.00000$$

$$\tan (90° - J) = \frac{0.55007 - 0.19442}{0.30117 - 0.00000}$$
$$= \frac{0.35565}{0.30117} = 1.18089$$

$$\text{arc} \tan 1.18089 = 49.74°$$
$$J = 90.0° - 49.74° = 40.26°$$

Since the geocentric inclination of the lunar orbit to the celestial equator (J_0) reaches a maximum value of about 28.5°, the topocentric inclination involves an angle which is approximately 11.8° greater than the geocentric. With this increased angle of inclination, and the maximum component-motions in declination which result, the apparent movement of the Moon in right ascension is reduced proportionately. As noted in chapter 2, the tidal day is thereby shortened, and the tide-amplifying effects are reduced.

2. Increase of Motion in Right Ascension and Lengthening of the Tidal Day at Times When the Moon is at an Extreme Declination

Contrastingly, in the perigee-syzygy situation which occurred with a mean epoch of 0500 G.c.t. on 1950 December 9, within 24 hours of an extreme lunar declination of −28°25′41.9″, the direct motion of the Moon in celestial longitude reached one of its largest possible values ($\Delta\lambda_☾ = 15°20'49.4''$, or 15.347°, between December 8.5 and 9.5). The hourly motion of the Moon in right ascension, $\Delta\alpha_☾ = 173.01^s$, likewise reached a maximum value for the entire year between 2130 and 2330 G.c.t. on December 9. (The exact repetition of the same maximum difference over a 3-hour period indicates a flattened peak on the declination curve, yielding a protracted maximum.) The semimonthly maximum declination of −28°25′41.9″ occurred at about 0500 G.c.t. on December 10. The value of $\pi_☾$ on December 9.0 G.c.t. was 61′27.09″.

The latter figure may be compared with the only slightly smaller parallax of 61′ 26.702″ associated with the great mid-Atlantic tidal flooding of 1962 March 6.5, and the somewhat larger value of 61′ 30.0009″ which accompanied the west coast tidal flooding of 1974 January 8.5—both discussed extensively in chapter 7.

However, the distinctive feature of the 1950 December 9 event was the extraordinarily large daily motion of the Moon in longitude on this date. As indicated, this was 15°21′ during the latter event compared with values of 15°15′ on the 1974 date and 15°14′ on the 1962 date.

Since the Moon is never far from the ecliptic, the rapid motion in celestial longitude is directly correlatable with the rapid motion of $173.01^{s}/^{msh}$ in right ascension which occurred on 1950 December 9. This was associated with the relatively large declination of −28°20′23.4″, increasing, within some 7 hours, to an extreme declination of −28°25′41.9″ for the month. For comparison, the declination of the Moon on 1962 March 6.5 G.c.t. was −7°42′05.42″, with a corresponding value of $\Delta\alpha_☾ = 146.543^s$. The maximum declination for this lunation was −19°50′19.35″, having a corresponding $\Delta\alpha_☾ = 147.955^s$. On 1974 January 8.5 G.c.t., the declination was +20°36′21.33″, with a value of $\Delta\alpha_☾ = 159.999^s$. The maximum declination for this lunation was +23°52′04.40″, with $\Delta\alpha_☾ = 163.965^s$.

The effect of an increased daily motion in longitude produced by the Moon's extremely close distance to the Earth in 1950, 1962, and 1974 thus was added to in 1950 by the effect of the relatively large declination at the time of perigee-syzygy, and a consequent increased motion in right ascension. The comparatively high declination at perigee-syzygy was, in turn, a function of the extreme declination of −28°25′41.9″ during the same lunation, caused by the coincidence of the lunar ascending node with the vernal equinox in this year.

The greater speed of movement in right ascension results in an extension of the necessary catch-up time, an increase in the length of the tidal day, and an augmentation of the tides.

The synoptic weather map for this 1950 December 9 date has been included among those grouped in chapter 7 to indicate a logical reason for the lack of attendant tidal flooding. Although the tides predicted for December 9–10 were appropriately high, in the complete absence of any strong, persistent, onshore winds on either the east or west coasts of North America, no major tidal flooding occurred.

Chapter 5.

The Essential Conditions for Achieving Amplified Perigean Spring Tides

As a direct follow-on to the theoretical discussions of the preceding chapter, it is noteworthy that certain other astronomical influences may act to produce both regular and irregular, but measurably significant increments in the positive and negative amplitudes of perigean spring tides—tending toward their ultimate maximization. In the present chapter, a brief summary of each such contributing influence will be followed by a quantitative analysis of its individual effects.

The General Concepts of Maximization of Perigean Spring Tides

One immediate cause of the secondary enhancement of tide-raising potential is a purely statistical one establishing, in varying degrees—over both quasi-periodic and aperiodic intervals of time—more exactly commensurable relationships between the synodic and anomalistic months. This close commensurability results, in turn, in an accompanying more precise spatial orientation between the line of syzygies and the line of apsides in the lunar orbit.

Increased dynamic factors acting upon the Moon's orbit because of the near-coincidence in the lines of gravitational force action connecting Earth, Moon, and Sun are responsible for an increased eccentricity and parallax, and hence a considerably closer proximity of the Moon to the Earth at perigee. This condition may also be accompanied, on occasion, by an independently originating, close alignment of the Moon and Sun in declination—whose influence is most effective when the two bodies are simultaneously at perigee-syzygy. Accordingly, for reasons involving both decreased lunar distance from the Earth and a mutually reinforcing combination of lunisolar forces, the tide-raising potential is augmented.

In accordance with Kepler's third law, these same circumstances also cause a temporarily increased apparent daily motion of the Moon in both longitude and right ascension. An appropriate catch-up motion by the rotating Earth becomes necessary in order to bring any given meridian on the Earth's surface into alignment with the axis of enhanced gravitational attraction of the Moon (and Sun). As will be seen, this required catch-up motion in turn increases the period of maximum tide-raising force application during the course of the tidal day.

The total tide-raising potential present is thus a function of two separate categories of influence: (1) those factors which, causing a very close alignment and a reinforcement of lunisolar gravitational attractions, coupled with an extreme proximity of the Moon (and Sun) to the Earth, *increase the tide-raising forces* exerted upon the Earth's waters; and (2) those factors which *lengthen the tidal day*—the interval within which these or other augmented tidal forces can act—and by this means likewise cause an increase in both the positive and negative amplitudes of the tides.

In dealing with the influences which act to generate increased high and low waters at time of perigee-syzygy, it is necessary to consider both of the above categories. Those factors involving purely force influences will be discussed in the present chapter; those associated with various astronomical influences producing changes in the length of the tidal day, often accompanied by other time-related effects, will be covered in chapter 6.

Factors Increasing the Intensities of the Tidal Forces Acting

(a) Unquestionably, one of the most important conditions—next to the positions of the Moon and Sun at perigee and perihelion, respectively—which serves strongly to increase the tidal forces acting is the presence of either or both of these two bodies near to, or directly in the local zenith (i.e., at an altitude of 90°). From a point of view related solely to the tide-raising potential, a greater vertical gravitational force exists under these conditions because the shortest distance between either the Moon or the Sun and the Earth's surface is at all times along a perpendicular to the surface. For reasons given in the preceding chapter, nowhere north or south of a declination of ±28.5°, respectively, can the Moon be perpendicular in altitude to the Earth's surface. Similarly, the Sun cannot reach the zenith if the latitude of the location is greater than ±23.5°. Since tidal forces vary inversely as the cube of the distance of the attracting body, this perpendicular distance to the Moon and its position in the local zenith are very important elements in establishing the greatest tide-raising potential.[a]

In considering relative tidal heights at any station, the location of the Moon directly over the Equator [b] is of further importance in another connection—that of diurnal inequality. In the equilibrium theory of the tides described in the appendix, it is seen that the tractive or horizontal force of the Moon tends to draw the waters of the Earth to a point where the line of gravitational attraction between Moon and Earth is perpendicular to the surface of the Earth. The maximum peak of the tidal bulge is produced in the vicinity of this sublunar point (together with an almost identical tidal bulge on the diametrically opposite side of the Earth). Because of several accelerating and retarding factors to be discussed in chapters 6 and 8, the Earth's two tidal bulges do not usually lie directly beneath, or in a position exactly 180° around the Earth in longitude from, the Moon. However, when the Moon is directly over the Equator twice each lunar month, the two crests of the hypothetical tidal force envelope (see fig. 5, appendix), do tend to be centered precisely in the equatorial plane.

The Earth's diurnal rotation occurs in a manner to carry any point on its surface in a direction which is always parallel to the Equator. When the tidal bulges lie on the Equator, therefore, any point on the Earth's surface in high-middle to low latitude rotates (between high and low water) into and out of the tidal bulges and through uniformly high tides on both sides of the Earth. There is no diurnal inequality. (See fig. 5 in the appendix.) Since the effect of increased tidal range is influential at certain locations in adding to the heights of perigean spring tides, this lack of a higher high water in equatorial type tides can, in some cases, be partially counterproductive to the increased lunar gravitational influence present with the Moon on the Equator.

(b) A second very important influence upon the available tide-raising force is the alignment of the Sun and Moon in the same (or exactly opposite) declination at the same time they are aligned in celestial longitude (at times of syzygy). The coincidence of perigee-syzygy with a common alignment of the Sun and Moon in declination adds appreciably to the tide-reinforcing effect caused by lunar proximity to the Earth. The possibility of *both* the Moon (in its orbit) and the Sun (in the ecliptic) being exactly aligned also in the plane of the celestial equator ($\delta = 0°$) at the same time they are aligned at perigee-syzygy is definitely less common. Such a situation is possible only when a lunar node coincides with one of the equinoxes—this action taking place (when within the angular limits defined in the footnote (c) on page 7) at the same time as a total lunar or solar eclipse.

However, the likelihood of the Sun and Moon becoming aligned at some declinational angle other than 0°, either on the same side of the Earth (at new moon) or on the opposite side (full moon), is not uncommon, considering that the Moon goes through its complete range of declination once in each tropical month of 27.321582 mean solar days (from vernal equinox to vernal equinox again).

(c) Seasonal factors also enter into the frequency of occurrence of various reinforcing combinations of gravitational force. As will be seen in table 13, the most favorable situation for increasing the forces acting at time of syzygy—thereby decreasing the distance of the Moon from the Earth—exists during the winter months. This is because the Earth is then closest to perihelion, permitting the Sun's gravitational force to be exerted to its fullest extent upon the tides. The Sun is, during the winter season of the Northern Hemisphere, at its maximum negative declinations. In order for the Moon to achieve a direct or opposite alignment in the Sun's declinational plane, it is necessary for the new moon to reach the same comparatively large negative declination as the Sun, or the full moon to attain an equal positive declination.

These declinational alignments will act to enhance the already greater tide-raising forces produced as the gravitational forces of Moon and Sun are combined at syzygy. Should the calendar year begin with the declinational

[a] It is important to note in this same respect, however, that the maximum horizontal or *tractive* tide-raising force is exerted upon the Earth's surface by the Moon along a small circle everywhere 45° from the current instantaneous position of the Moon. (See fig. 35 and the accompanying discussion.)

[b] As will be seen in chapter 6, the apparent westward (rising and setting) motion of the Moon caused by the Earth's rotation is the greatest when it is on the celestial equator, but the Moon's apparent eastward motion in right ascension due to its real motion in orbit is then the least—factors of importance in connection with relative catch-up times.

plane of the Moon close to that of the Sun, while the Sun itself is near perigee with the Earth, (i.e., at perihelion) an additional amount of tide-raising force is produced.

A Quantitative Evaluation of the Various Tide-Maximizing Factors

Table 12 illustrates the effect upon the proximity of the Moon to the Earth resulting from the astronomical condition of perigee-syzygy when this geometrical alignment is combined with the location of both the Moon and the Sun on or near the *celestial equator*. The Sun, in its apparent annual motion along the ecliptic, crosses the celestial equator around March 21 and September 23 of each year—at the vernal and autumnal equinoxes, respectively.

Since the Moon is never more than 5°9′ from the ecliptic, the time at which the Moon, while at perigee-syzygy, can be simultaneously near the celestial equator will always be close to one of these dates, a fact confirmed in table 12. This table lists 45 cases of perigee-syzygy in which the separation between the two components is $\leq$ 24 hours and the declination of the Moon is $\leq +1°$ (one case of 1.1° is included). The additional solar gravitational and perturbational forces acting on the Moon when the Sun is in, or very nearly in, the same plane as the Moon around the times of the equinoxes—as shown by the relatively larger lunar parallaxes resulting under these conditions—are clearly revealed by these data.

However, a comparison is also desirable between this table and table 13—which shows the effects of the additional gravitational force of the Sun on the lunar orbit caused by the occurrence of perigee-syzygy close to the time of *perihelion*. Such a comparison reveals that the latter situation is far more effective, in increasing the lunar parallax, if the Sun and Moon are coplanar in declination. As examples of this, in table 13, note especially the large value of the parallax for the date 1912 January 4, despite the very high lunar declination of +27.6°, and again for 1930 January 14, with a lunar declination of +26.0°. Both dates are, of course, very close to that of perihelion, when the Sun's gravitational effect reaches its maximum.

Finally, a comparison can be made between the data of table 13 and those of table 14, which show the effect upon the lunar parallax of a situation in which the Moon is at one of the two *nodes* of its orbit (i.e., crossing the ecliptic) at the time of both perihelion and perigee-syzygy. The circumstance under which the Moon is simultaneously in the plane of the ecliptic, and either precisely or very nearly aligned in celestial longitude with the Sun is that of a total solar or total lunar eclipse. The type of eclipse which occurs depends upon whether the Moon lies between the Earth and the Sun, (at new moon) or on the opposite side of the Earth from the Sun (at full moon), respectively.

The combination of the gravitational forces of the Earth and Sun, exerted along nearly the same axes in λ and β, creates an additional perturbing force upon the lunar orbit. However, as will be seen in table 14, the effect upon an increase in the lunar parallax is not as pronounced as in either of the two preceding examples.

This is due in some degree to the fact that, in the case of a total solar eclipse, the gravitational forces of the very massive but vastly more distant Sun and the less massive but closer Earth—exerted in opposite directions on the Moon's orbit—are partially compensating. On the other hand, the production of a maximum lunar parallax is the result of undiminished, maximized solar forces and perturbations.

Consider, for example, the large but not extreme lunar parallaxes at the times of the solar eclipses of 1967 November 2 and 1985 November 12 in table 14; also the comparatively large parallax values in the following cases chosen from table 1, associated with coastal flooding.

Date and Time (G.c.t.) of Conjunction in Longitude	Maximum Duration of Eclipse Totality	$\pi_☾$ at Syzygy	$\delta_☾$ at Syzygy	Separation-Interval P–S
1901 April 18 2200^h	6.5^m.	61′24. 3″	+12. 8°	−37^m
1949 October 21 2100^h	(Partial). .	61′23. 4″	−11. 8°	−6^h

All four cases have a perigee-syzygy alignment within 6^h or less. The first two cases also are approaching the time of perihelion. However, the further coincidence of lunar opposition and very close proximity in time to perihelion necessary to achieve either an extreme or a maximum proxigee-syzygy (table 13) is lacking.

Summary of Relative Gravitational Force Influences

Assuming a common limiting condition in which the separation between perigee and syzygy is $\leq 24^h$:

A situation in which the Moon (passing through one of the two lunar nodes at times of solar or lunar eclipse) crosses the ecliptic at the same time the Earth is near perihelion (between November 2 and February 26 in table 14) is, in general, not as effective in increasing the lunar parallax as either—

TABLE 12.—*Selected Cases of Perigee-Syzygy, Showing the Relationship Between the Equinoctial (Near-Equatorial) Position of the Moon and the Lunar Parallax Over the 400-Year Period 1600–1999*

Primary Limiting Range for Perigee-Syzygy Separation:	$P-S \leq \pm 24^h$	
Secondary Limiting Range for Proximity of Moon to Celestial Equator:	$\delta_☾ \leq \pm 1°$	
Resulting Bracketing Ranges for Proximity of Perigee-Syzygy to Vernal or Autumnal Equinoxes:	Spring dates	3/8–4/2
	Autumn dates	9/9–10/6

Date	Time (G.c.t.) of syzygy	Lunar phase	Horizontal parallax at syzygy	$\delta_☾$ at syzygy	Perigee — syzygy
	h		′ ″	°	h
1617 Sept. 15	4	F	61 19.0	−0.6	+13
1621 Mar. 8	2	F	61 18.3	+0.3	−16
1626 Mar. 27	19	N	61 20.3	+0.3	−10
1635 Mar. 18	19	N	61 25.1	+0.6	+ 1
1649 Mar. 28	11	F	61 8.1	+0.8	+19
1662 Mar. 20	2	N	61 10.8	−0.3	+17
1675 Mar. 11	18	F	61 19.8	−0.7	+13
1679 Mar. 12	9	N	61 26.3	−0.4	− 2
1679 Sept. 20	2	F	61 20.0	+0.6	+12
1684 Mar. 31	2	F	61 27.8	+0.1	+ 4
1696 Sept. 11	9	F	61 25.4	−0.1	− 6
1701 Oct. 2	2	N	61 26.0	+0.3	− 1
1705 Oct. 2	17	F	61 14.8	+0.3	−16
1710 Mar. 15	9	F	61 27.8	+0.3	− 3
1718 Sept. 24	9	N	61 5.3	+0.8	−20
1745 Sept. 25	17	N	61 23.2	−1.0	− 5
1750 Mar. 8	8	N	61 23.0	−0.5	+ 8
1759 Oct. 6	9	F	61 20.9	+0.5	+13
1780 Sept. 28	7	N	61 4.2	+0.7	−20
1789 Mar. 11	14	F	61 6.8	−0.9	−22
1794 Mar. 31	7	N	61 12.3	+0.9	−16
1820 Sept. 22	7	F	61 22.1	+0.2	− 9
1825 Sept. 12	15	N	61 9.5	−0.4	+18
1830 Mar. 24	15	N	61 19.7	+0.2	+10
1834 Oct. 2	23	N	61 22.9	+0.7	+ 9
1847 Mar. 16	21	N	61 23.1	+0.2	− 8
1860 Sept. 15	6	N	61 24.9	−0.7	+ 3
1864 Sept. 15	21	F	61 18.8	+0.8	−12
1869 Mar. 27	22	F	61 7.0	+0.8	−21
1869 Oct. 5	14	N	61 23.5	−0.6	− 7
1874 Sept. 25	22	F	61 7.4	−1.0	+20
1883 Mar. 9	4	N	61 8.6	−0.8	+19
1892 Mar. 28	13	N	61 21.2	+0.3	+ 9
1895 Sept. 18	21	N	61 14.4	+0.6	−13
1900 Sept. 9	5	F	61 18.4	−1.0	+14
1905 Sept. 28	22	N	61 7.6	+0.7	+19
1922 Sept. 21	5	N	61 24.0	+0.8	+ 1
1927 Apr. 2	4	N	61 24.5	0.0	− 6
1935 Sept. 12	20	F	61 27.1	−0.3	− 2
1939 Sept. 13	11	N	61 9.4	+1.0	−17
1944 Oct. 2	4	F	61 21.2	−0.9	−11
1953 Mar. 15	11	N	61 18.2	+1.1	−13
1967 Mar. 26	3	F	61 26.7	+0.6	+ 5
1993 Mar. 8	10	F	61 30.0	+0.2	− 2
1998 Mar. 28	3	N	61 24.7	+0.7	+ 4

TABLE 13.—*Compilation of All Cases of Extreme Proxigee-Syzygy Occurring Over the 400-Year Period 1600–1999, Showing the Combined Influence of Perihelion, Lunar Opposition, and Approximately Coplanar Lunisolar Declinations in Reducing the Perigee-Syzygy Separation and Increasing the Lunar Parallax* (see text explanation).

Selected Lower Limit for Lunar Parallax:	$\pi \geq 61'29.0''$
Resulting Limiting Range for Perigee-Syzygy Separation:	$P-S \leq \pm 5^h$
Resulting Bracketing Range for Proximity of Perigee-Syzygy to Perihelion:	10/31–3/8

Date	Phase	Parallax at syzygy		Declination	Perigee minus syzygy	Parallax at perigee		Declination
(G.c.t.)		′	″	°	h	′	″	°
1603 Jan. 27	FM	61	29.9	+14.1	+5	61	30.2	+13.3
1609 Nov. 11	FM	61	30.4	+13.3	−1	61	30.4	+13.2
1627 Nov. 22	FM	61	30.6	+15.9	+2	61	30.7	+16.2
1629 Jan. 9	FM	61	29.8	+22.8	−1	61	29.8	+22.8
1630 Feb. 27	FM	61	29.7	+12.9	−3	61	29.9	+13.7
1645 Dec. 3	FM	61	30.3	+17.8	+4	61	30.6	+18.2
1647 Jan. 20	FM	61	29.6	+20.8	+1	61	29.6	+20.7
1671 Nov. 16	FM	61	30.3	+23.2	−2	61	30.4	+22.8
1673 Jan. 3	FM	61	29.9	+26.3	−5	61	30.2	+26.7
1689 Nov. 26	FM	61	30.9	+25.6	0	61	30.9	+25.6
1691 Jan. 14	FM	61	30.5	+24.7	−2	61	30.6	+25.1
1707 Dec. 9	FM	61	31.0	+27.1	+3	61	31.1	+27.3
1709 Jan. 25	FM	61	30.5	+22.3	0	61	30.5	+22.4
1725 Dec. 19	FM	61	30.4	+27.8	+4	61	30.7	+27.9
1727 Feb. 6	FM	61	30.0	+19.2	+2	61	30.0	+18.8
1751 Dec. 2	FM	61	29.4	+21.4	−2	61	29.5	+21.3
1753 Jan. 19	FM	61	30.8	+15.4	−4	61	31.0	+15.9
1769 Dec. 13	FM	61	29.7	+22.5	1	61	29.7	+22.5
1771 Jan. 30	FM	61	31.1	+12.8	−2	61	31.2	+13.1
1787 Dec. 24	FM	61	29.4	+22.8	+3	61	29.6	+22.6
1789 Feb. 10	FM	61	30.9	+ 9.5	+1	61	30.9	+ 9.5
1807 Feb. 22	FM	61	30.1	+ 5.8	+2	61	30.2	+ 5.2
1813 Dec. 7	FM	61	30.3	+18.9	−2	61	30.4	+18.6
1830 Oct. 31	FM	61	29.7	+10.0	+2	61	29.8	+10.3
1831 Dec. 19	FM	61	30.8	+19.6	0	61	30.8	+19.6
1849 Dec. 29	FM	61	30.8	+19.4	+2	61	30.8	+19.4
1868 Jan. 9	FM	61	30.1	+18.4	+3	61	30.3	+18.2
1875 Dec. 12	FM	61	30.5	+27.9	−4	61	30.8	+27.6
1893 Dec. 23	FM	61	31.4	+28.2	−2	61	31.4	+28.2
1912 Jan. 4	FM	61	31.6	+27.6	+1	61	31.6	+27.6
1930 Jan. 14	FM	61	31.3	+26.0	+2	61	31.4	+25.8
1948 Jan. 26	FM	61	30.4	+23.6	+4	61	30.8	+23.0
1954 Nov. 10	FM	61	29.7	+20.8	−1	61	29.7	+20.7
1972 Nov. 20	FM	61	30.1	+23.6	+1	61	30.1	+23.8
1974 Jan. 8	FM	61	30.0	+20.5	−2	61	30.0	+20.7
1975 Feb. 26	FM	61	30.0	+ 4.4	−3	61	30.2	+ 5.2
1990 Dec. 2	FM	61	30.0	+25.7	+3	61	30.1	+25.9
1992 Jan. 19	FM	61	29.9	+18.6	+1	61	30.0	+18.5
1993 Mar. 8	FM	61	30.0	+ 0.2	−2	61	30.1	+ 0.6

A situation of perigee-syzygy with the Moon simultaneously in or near the plane of the celestial equator ($\delta_☾ \leq 1°$) and close to the position of one of the two equinoxes (between March 8 and April 2, or September 9 and October 6 in table 12), or—

A situation in which the alignment of perigee-syzygy occurs concurrently with the Earth at or near perihelion, the Moon at opposition, and the Sun in the same declinational plane as the Moon (see table 13). The influence of such combined perigee-syzygy, lunar opposition, and lunisolar declinational alignments occurring in the period near perihelion—producing the largest geocentric horizontal parallaxes of the Moon over the entire 400-year period between 1600 and 1999—will be discussed further in the following section.

TABLE 14.—*Selected Cases of Perigee-Syzygy Occurring Simultaneously at a Lunar Node (Total Solar Eclipse) and Near Perihelion, Showing the Combined Effect of These Factors Upon the Lunar Parallax Over the 100-Year Period 1900–1999*

Limiting Range for Perigee-Syzygy Separation:	$P-S \leq \pm 24^h$
Limiting Range for Celestial Latitude of Moon at Conjunction (Total Solar Eclipse Certain):	$\beta_☾ < \pm 1°24'36''$
Consequent Limiting Dates for Proximity of Perigee-Syzygy to Perihelion:	11/2–2/26

Date	G.c.t. of conjunction in longitude	Maximum duration of total phase	Horizontal parallax at syzygy	$\delta_☾$	Perigee—syzygy
	h	m	′ ″	°	h
1908 Jan. 3	2144	4.5	61 16.1	−22.7	+15
1926 Jan. 14	0635	4.4	61 12.4	−21.2	+17
1944 Jan. 25	1525	4.4	61 8.3	−18.9	+20
1961 Feb. 15	0811	2.9	61 5.5	−11.9	−21
1962 Feb. 5	0011	4.3	61 3.5	−15.9	+22
1967 Nov. 2	0548		61 25.3	−15.5	− 4
1979 Feb. 26	1647	3.0	61 9.4	− 7.9	−19
1985 Nov. 12	1420		61 26.5	−18.7	− 1
1994 Nov. 3	1336	4.6	61 21.0	−15.4	+10

Astronomical Influences Producing Uneven Heights Among Perigean Spring Tides; Lack of a Current Procedure for Variable-Intensity Classification

The preceding three examples and their accompanying tables offer a straightforward empirical confirmation of various possible combinations and reinforcements of the gravitational forces of the Moon and Sun. These gravitational reinforcements act, in turn, to produce corresponding amplifications in the tide-raising forces present. In a general expansion of the preceding principles, it is interesting to consider all possible interrelationships between these forces which act toward an ultimate maximization of perigean spring tides. The statistical likelihood of such extreme tidal enhancements is necessarily spread over longer and less regular periods of time, due to the decreasing chance for commensurability among the greater number of factors involved.

Among the force-related aspects which may provide a multisource amplification of perigean spring tides are those itemized below.

Assuming a condition of perigee-syzygy, with the Moon and Sun aligned in longitude (λ) or right ascension (α), but not initially in either declination (δ) or celestial latitude (β), tidal forces are increased when:

(a) The Moon is at one of its two nodes, crossing the ecliptic and therefore (at syzygy) is simultaneously in both the same latitudinal and longitudinal planes as the Sun, but not in the plane of the celestial equator;

(b) The Moon and the Sun are in the same declinational plane—either on the Earth's near side (with similar algebraic signs) or on its far side (with opposite algebraic signs). Both bodies are coplanar, in δ as well as in $\dot{\alpha}$ (or λ), but not in β—and neither is over the celestial equator. This condition can be either additive or, under certain circumstances (see the second following section), counterproductive in terms of tide-raising forces.

(c) The Moon and—at perigee-syzygy—the Sun also, are in the zenith of the place. The result is a reinforcement of their respective tide-raising potentials at perigee and along a common axis in longitude by an increased lunar gravitational force produced by the Moon's geometrically least distance at the sublunar position on the surface of the Earth. The effect of lunar augmentation (fig. 25A) may also be involved to a slight degree.

(d) The Moon is crossing the celestial equator at a time close to either of the two equinoxes, putting it in the equatorial plane ($\delta=0°$) very nearly at the same time at which the Sun is crossing this plane. Various degrees of proximity to the times of the equinoxes may be involved. The two bodies are also very nearly aligned in α or λ (at syzygy).

(e) The Moon is at one of its two nodes (occurring every 9.3 years) and crossing the ecliptic at a time coinciding with one of the two equinoxes. This puts the Moon in the same latitudinal and declinational planes ($\beta=0°$, $\delta=0°$) as that of the Sun, simultaneously with these two bodies being aligned in the same or opposite longitude or right ascension (at syzygy).

(f) In all except cases (d) and (e), the tide-raising force produced as the result of the conditions present may be further augmented if the given circumstances occur when the Earth is also near perihelion (i.e., the Moon is close to solar perigee) and especially if the Moon is at full phase.

(g) The full moon is at one of its two nodes (i.e., in the plane of the ecliptic at the time of perigee-syzygy, putting it simultaneously in the same latitudinal and longitudinal alignments with the Sun), as well as at its closest monthly approach to the Earth. If these various circumstances occur coincidentally with the time at which the Earth reaches perihelion, the Sun (at its closest annual position to the Earth) also exerts a greater attraction. The added solar tide-raising force directly reinforces that of the Moon, which is nearly colinear with the Sun in both longitude and latitude. Subject to this coincidence in orientation between the line of nodes and line of apsides of the Moon's orbit, together with the line of apsides of the Earth's orbit and the common line of syzygies—all forming nearly the same axis, and with the respective secondary bodies at their lower apse positions—the greatest possible lunar parallaxes result.[e]

Upon more frequent occasions, closely commensurate relationships between the synodic and anomalistic months exist as the result of which the separation-interval between perigee and syzygy becomes very small, perturbations and the lunar parallax correspondingly large, and the Moon's perigee distance from the Earth is significantly reduced. For purposes of detailed analysis, this situation involving both an extremely close perigee-syzygy alignment and minimum lunar distance from the Earth is here given the designation *proxigee-syzygy.* The corresponding *proxigean spring tides* will be discussed in detail in chapter 8, along with a suggested classification terminology based on quantitative factors.

If the conditions specified in (g) above take place simultaneously, the resulting tides have somewhat indefinitely been described in the literature as *maximum perigee springs,*[1, 2, 3, 4] a very rare circumstance which is predicted to have occurred last and most recently near the perihelion of A.D. 1340. This designation should not be confused with that of the extreme tides categorized in chapter 8 as *maximum proxigean spring tides*—a specific astronomicaly quantified entity in the nomenclatural system proposed. According to these rigorous definitions, the name *ultimate maximum proxigean spring tides* has been given to the absolute high tide experienced in A.D. 1340.

[e] The perigee-syzygy of 1912 January 4, 1300 e.t. (with a separation-interval of only +6.5 *minutes*) is an approximate example, although $\beta_{☾}$ was very nearly 5° at that time. The lunar parallax at the mean epoch of perigee-(proxigee-) syzygy was 61′31.6″, compared with the theoretically highest possible value of 61′32″. An atmospheric high pressure system prevailed on the west coast, and offshore winds south of a low prevented tidal flooding in New England. Although a weak low lay over eastern Canada, the normal completely ice-free season here extends only from May 1 to November 30. (See fig. 72.)

Perigean Spring and Other Tidal Equivalents in International Terminology

Although no official nomenclatural counterpart exists in international hydrographic dictionaries[d] or multilingual technical glossaries of the French, German, Dutch, Spanish, Russian, and other languages for the term "perigean spring tides," the German literal translation is, for example, *die Springtiden die während des Perigäums eintreten.* While no direct descriptor term is provided in the French language for "perigean spring tides," "equatorial tides" are distinguished as *marées équatoriales,* "equinoctial tides" are designated as *marées de équinoxe,* "solstitial tides" are know as *marées de solstice,* and "perigean tides" as *marées de périgée.* The German equivalents are *Äquatorialgezeiten, Gezeiten während der Tagundnachtgleiche, Gezeiten während des Sonnenhöchststandes,* and *Gezeiten während des Perigäums.*

The respective expressions in the above five languages for ordinary "spring tides" are *marées de vive eau, Spring-tiden, springtij, mareas vivas o de sicigias,* and СИЗИГИЙНЫЕ ПРИЛИВЫ. The multilingual equivalents for the combining form "perigee-syzgy" are: *périgée-syzygie, Perigäum-Syzygium, perigeum-syzigien, perigeosicigia,* and ПЕРИГЕЙ-СИЗИГЍЯ. In addition, certain other nonuniversal terms are available for various of the tide-raising conditions listed in the preceding section.

Thus, the tides produced under the circumstances associated with (d) in this list are termed, in English, *equinoctial spring tides.* The French, German, and Spanish equivalents are *marées de vive eau d'équinoxe, Springtide zur Zeit der Tagundnachtgleiche,* and *mareas equinociales de primavera.*

As noted in the same paragraph, the position of perigee-syzygy (implying in part the alignment in longitude of both the Moon and Sun)—together with the lunar crossing of the celestial equator—may occasionally occur within a short time of one of the equinoxes (see table 12). This situation is described by the French as *la grande marée d'équinoxe* (high equinoctial spring tide), or *marée extraordinaire de vive eau d'équinoxe.* Typical examples are those of

[d] Cf. International Hydrographic Organization, *Hydrographic Dictionary,* Special Publication No. 32 (2d ed., in five languages), Monaco, 1951; (3d ed., Part I—English-French), Monaco, 1974.

1918 March 12, 2000 G.c.t. (e.t.)[e] ($\delta_☾=+1.2°$), 1935 September 12, 2000 G.c.t. ($\delta_☾=-0.3°$), 1967 March 26, 0300 G.c.t. ($\delta_☾=+0.6°$), and 1976 March 16, 0300 G.c.t. ($\delta_☾=-1.7°$). The last example also provides a documented case of tidal flooding, listed in table 1 and described in chapter 7.

Compensating and Counterproductive Tidal Force Influences

Finally, from a contrasting, tide-*reducing* point of view, there is one factor which may act to neutralize, or equalize in a compensating fashion, the effective forces of Sun and Moon as a consequence of the relative declinations of these two bodies.

The tide-raising force of the Moon, because of the satellite's much closer distance to the Earth than to the Sun, and despite the Moon's much smaller mass compared with that of the Sun, averages 2.2 times that of the Sun. The tide-raising force of the Sun, accordingly, is 0.45 that of the Moon. Thus, in a relative sense, in considering the forces exerted by the Sun and Moon when they are in longitudinal alignment at syzygy, a difference of approximately 11° in declination of the Moon corresponds to a difference of approximately 23½° in declination of the Sun.

At new moon, if the Moon has a declination of 23½° north and the Sun a declination of 11° south—or the Moon has a declination of 11° north and the Sun a declination of 23½° south—the individual gravitational forces counteract. Two opposite tidal bulges are created which are symmetrically disposed north and south of the Equator, nullifying the effect of diurnal inequality.

Similarly, at full moon, if the Sun has a declination of 23½° north and the Moon likewise has a declination of 11° north—or the Sun has a declination of 23½° south and the Moon a declination of 11° south—their forces compensate and two tidal bulges, again symmetrically disposed with respect to the Equator, are produced.

Although the diurnal inequality (see appendix) disappears at these times at any geographic latitude, the important consideration in terms of the present discussion is that the lunar and solar gravitational forces offset, rather than reinforce each other.

Variation in Parallax and Orbital Curvature with Lunar Configuration

Table 13 represents a sample section from a master computer printout later to be discussed (table 16), and shows all cases of perigee-syzygy during the 400-year period 1600–1999 in which the accompanying lunar parallax is equal to, or greater than 61′29.0″. In this table, column 1 indicates the year and date of the event to the nearest day; column 2 indicates the phase of the Moon at the time of perigee-syzygy; column 3 shows the parallax at the nearest hour to new or full moon; column 4 tabulates the corresponding declination at the time of new or full moon; column 5 shows the separation-interval between perigee and syzygy, in hours, in the sense perigee minus syzygy; column 6 notes the parallax at the exact instant of perigee; and column 7 gives the declination of the Moon for this same time. Ephemeris time, which is very nearly equal to Greenwich civil time (see explanatory remarks on page 13), is used throughout. Table 13, together with figs. 37–38, will be used later in this chapter to illustrate a very interesting phenomenon of phase distinction in connection with the Moon's changing distance from the Sun.

In dealing with the Earth-Moon system alone in terms of tides, the gravitational force of the Moon may be thought of as exerted along a force vector extended from the center of the Moon to the center of the Earth. In this tidal model, the difference in magnitude between the tide-raising forces acting upon two positions located at the Equator on directly opposite sides of the Earth is of very little consequence. Quantitatively, the tide-raising force producing the direct tide (fig. 2, appendix) is only 0.000000005 greater than that producing the opposite tide, since two points in diametrically opposite positions on the surface of the Earth are only 2 × 6,378.388 km = 13,757 km (7,927 mi) apart.

However, in dealing with the changing lunar distance from the Sun when the Moon is in opposite extremes (with respect to the Sun) of its orbit around the Earth, the difference is 2 × 384,404 km = 768,808 km (477,714 mi). This is no longer insignificant, gravitationally speaking, since the inverse cube of this distance is involved in the resultant tide-raising force (different by one power of the distance from the inverse square law of gravitation).

In discussing the solar gravitational forces heretofore, consideration has been given to the Sun's gravitational influence on the tides only in terms of its modification of the Moon's gravitational attraction on these tides, without regard to any disturbances the Sun's gravitational attraction might impose on the positions or motions of the Moon itself. The further assumption has been made that, in accordance with Newton's law of gravitation, the Moon is subject to a centrally acting force varying inversely as the square of the Moon's distance from the Earth. In the presence of the Sun's additional gravitational force, such is not actually the case,

[e] Because of the span of years involved between these dates, in which the time-zone designations G.m.t., G.c.t., u.t., and e.t. have variously been used (see page 13), the times indicated have been converted consistently to the e.t. of table 16, which differs but slightly from G.c.t.

and consideration must be given to the dynamic problems of three bodies. At this point, the issue involved is the gravitational force of the Earth and Sun on the Moon rather than the tide-raising force of the Moon and Sun on the Earth.

Since the tide-raising forces vary inversely as the cube of the distance between the Moon (or Sun) and the Earth, these forces may increase enormously when the Moon's distance from the Earth is reduced. A similar effect, although not to such a prominent degree, occurs during the Earth's closest annual approach to the Sun at perihelion. However, because of the greater proximity of the Moon to the Earth compared with that of the Sun, the tide-raising force of the Moon at any time is 2.2 times that of the Sun.

Comparative Effects of Various Lunisolar Configurations Upon Lunar Distance from the Earth and the Curvature of the Lunar Orbit

The dynamic effect of perigee-syzygy in increasing the eccentricity of the lunar orbit, as well as the considerable reduction in the distance of the Moon from the Earth at a time of very close perigee-syzygy, can be seen in table 15. On 1974 January 8.5, in an instance shown from table 13 to have an unusually large parallax (61′30.0″ at syzygy or 61′30.1″ at maximum value)—and appropriately defined in table 22 as a case of "extreme proxigee-syzygy"—the separation-interval between perigee and syzygy (at full moon) was only -1^h36^m. The corresponding values of true geocentric distance of the Moon from the Earth for a week on either side of this perigee-syzygy date, as taken from *The American Ephemeris and Nautical Almanac,* are also indicated in table 15.

From the same table, the variation of the Earth-Moon distance before, during, and after this closely aligned perigee-syzygy situation may profitably be compared with similar data for an instance of perigee-quadrature occurring around 1974 November 7–8. In this case, the separation between perigee and quadrature (at last quarter moon) was +25 hours.

Finally, an interesting comparison also is possible between the values of the Earth-Moon distance at perigee-syzygy and the respective distances at the apogee-syzygy alignments next preceding it on 1973 December 25.2 (at new moon) and consecutively following, on 1974 January 22.5 (also at new moon). The corresponding component separation-intervals in these latter two cases are +31 hours and +37 hours. All values for distance in these various tabulations are given in units of Earth-radii (one Earth-radius is equal to 6,378.-160 kms at the Earth's Equator).

One immediate indication from these comparisons is, of course, the fact that the particular time of occurrence of *perigee* is of much greater importance in establishing the actual time of the least distance of the Moon associated with perigee-syzygy than is the component of *syzygy*. The tables also reveal an interesting relationship in comparing lunar distance data resulting from this near-coincidence of perigee and syzygy with like data from either the preceding or following apogee. The comparison between the respective values at perigee-syzygy and apogee-syzygy yields a far greater range in the distances of the Moon from the Earth than does a similar comparison between the lunar distances at either perigee-syzygy or apogee-syzygy and those at perigee-quadrature.

Thus, the Earth-Moon distances range from 63.733 to 55.901 (or 7.832 Earth-radii) in comparing the apogee-syzygy of 1973 December 25.2 with the perigee-syzygy of 1974 January 8.5, and from 55.901 to 63.728 or a nearly similar 7.827 Earth-radii) between the perigee-syzygy of 1974 January 8.5 and the apogee-syzygy of 1974 January 22.5.

Much smaller differences are obtained in comparing the distances of the Moon at the time of the perigee-quadrature of 1974 November 7.7 with those occurring at the full moon of 1974 October 31.1 or the new moon of 1974 November 14.0. The latter syzygy dates occur nearly symmetrically on either side of perigee-quadrature, with syzygy then at its greatest possible separation-interval (approximately 7 days from perigee). The geocentric distances of the Moon vary from 60.521 to 58.021 Earth-radii in the first case and from 58.021 to 59.756 Earth-radii in the second (providing individual ranges of only 2.500 and 1.735 Earth-radii, respectively).

In like manner, a comparison can be made of the various geocentric distances (and their differences) around such significant times as: (1) apogee-syzygy; (2) apogee-quadrature; (3) ordinary syzygy (separated to the greatest extent possible from either perigee or apogee); (4) ordinary quadrature (subject to a similar maximum separation from the line of apsides); (5) perigee-quadrature; and (6) perigee-syzygy. The general results obtainable from the analysis of examples of changing geocentric distances of the Moon previously cited show that: (a) the occupied portion of the orbit has a considerably smaller curvature at syzygy than at ordinary quadrature, and (b) an even smaller orbital curvature exists at perigee-syzygy than at ordinary syzygy. As above defined, the

TABLE 15.—*True Geocentric Distance of the Moon*

	Date	Distance (Earth-radii)		Date	Distance (Earth-radii)		Date	Distance (Earth-radii)
	1973			1974			1974	
	Dec. 9. 0	56. 690 165		Jan. 0. 0	62. 088 438		Oct. 24. 0	63. 390 466
	9. 5	56. 444 821		0. 5	61. 729 311		24. 5	63. 412 087
P-S	10. 0	56. 268 904		1. 0	61. 336 876		25. 0	63. 384 060
Dec. 10. 5	10. 5	56. 166 337	FQ	1. 5	60. 914 330		25. 5	63. 308 309
FM, 10. 1	11. 0	56. 138 847	Jan. 1. 8	2. 0	60. 465 972		26. 0	63. 187 606
	11. 5	56. 185 898		2. 5	59. 997 253		26. 5	63. 025 490
	12. 0	56. 304 752		3. 0	59. 514 777		27. 0	62. 826 173
	12. 5	56. 490 670		3. 5	59. 026 261		27. 5	62. 594 426
	13. 0	56. 737 208		4. 0	58. 540 433		28. 0	62. 335 460
	13. 5	57. 036 598		4. 5	58. 066 867		28. 5	62. 054 791
	14. 0	57. 380 166		5. 0	57. 615 743		29. 0	61. 758 098
	14. 5	57. 758 755		5. 5	57. 197 537		29. 5	61. 451 073
	15. 0	58. 163 125		6. 0	56. 822 650		30. 0	61. 139 269
	15. 5	58. 584 304		6. 5	56. 500 972		30. 5	60. 827 956
	16. 0	59. 013 875		7. 0	56. 241 432	FM	31. 0	60. 521 986
LQ	16. 5	59. 444 197		7. 5	56. 051 541	Oct. 31. 1	31. 5	60. 225 667
Dec. 16. 7	17. 0	59. 868 552	P-S	8. 0	55. 936 984		Nov. 1. 0	59. 942 676
	17. 5	60. 281 232	Jan. 8. 5	8. 5	55. 901 289		1. 5	59. 675 989
	18. 0	60. 677 566	FM 8. 5	9. 0	55. 945 614		2. 0	59. 427 850
	18. 5	61. 053 896		9. 5	56. 068 676		2. 5	59. 199 786
	19. 0	61. 407 518		10. 0	56. 266 830		3. 0	58. 992 645
	19. 5	61. 736 588		10. 5	56. 534 278		3. 5	58. 806 686
	20. 0	62. 040 010		11. 0	56. 863 408		4. 0	58. 641 689
	20. 5	62. 317 303		11. 5	57. 245 202		4. 5	58. 497 092
	21. 0	62. 568 467		12. 0	57. 669 689		5. 0	58. 372 146
	21. 5	62. 793 845		12. 5	58. 126 401		5. 5	58. 266 063
	22. 0	62. 993 981		13. 0	58. 604 803		6. 0	58. 178 171
	22. 5	63. 169 502		13. 5	59. 094 665		6. 5	58. 108 031
	23. 0	63. 320 995		14. 0	59. 586 368		7. 0	58. 055 549
	23. 5	63. 448 913		14. 5	60. 071 146	P-Q	7. 5	58. 021 031
	24. 0	63. 553 492	LQ	15. 0	60. 541 247	Nov. 7. 7	8. 0	58. 005 212
	24. 5	63. 634 691	Jan. 15. 3	15. 5	60. 990 037	LQ, 7. 1	8. 5	58. 009 231
A-S	25. 0	63. 692 157		16. 0	61. 412 040		9. 0	58. 034 571
Dec. 25. 2	25. 5	63. 725 208		16. 5	61. 802 935		9. 5	58. 082 954
NM, 24. 6	26. 0	63. 732 848		17. 0	62. 159 514		10. 0	58. 156 198
	26. 5	63. 713 792		17. 5	62. 479 601		10. 5	58. 256 059
	27. 0	63. 666 530		18. 0	62. 761 965		11. 0	58. 384 050
	27. 5	63. 589 391		18. 5	63. 006 198		11. 5	58. 541 266
	28. 0	63. 480 646		19. 0	63. 212 594		12. 0	58. 728 214
	28. 5	63. 338 606		19. 5	63. 382 019		12. 5	58. 944 672
	29. 0	63. 161 745		20. 0	63. 515 778		13. 0	59. 189 579
	29. 5	62. 948 824		20. 5	63. 615 481	NM	13. 5	59. 460 977
	30. 0	62. 699 026		21. 0	63. 682 919	Nov. 14. 0	14. 0	59. 755 984
	30. 5	62. 412 089		21. 5	63. 719 945		14. 5	60. 070 829
	31. 0	62. 088 438	A-S	22. 0	63. 728 363		15. 0	60. 400 921
	31. 5	61. 729 311	Jan. 22. 5	22. 5	63. 709 838		15. 5	60. 740 967
	32. 0	61. 336 876	NM, 23. 5	23. 0	63. 665 816		16. 0	61. 085 107

"ordinary" cases are separated by a maximum distance in time from perigee.

However, a more sensitive measure of changes in figure of the lunar orbit is provided by use of hourly values of the lunar parallax, tabulated in *The American Ephemeris and Nautical Almanac* since the 1972 edition. One important fact must be borne in mind in this transfer from the direct measurement of the Moon's geocentric distance in Earth-radii to the inverse measure of this distance by use of parallax values indicated in minutes and seconds of arc: namely, that the two methods and their corresponding units also indicate a *change* in distance in exactly opposite ways.

Secondly, in interpreting the figure of the lunar orbit in general, a change in the major axis of the orbit through induced perturbations is necessarily accompanied by a change in orbital size and shape, but the exact configuration assumed is also dependent upon resultant or simultaneous changes in the orbital eccentricity. The eccentricity bears no one-to-one relationship with either the local or instantaneous curvature of the orbit. Eccentricity (e) is a function of the relative lengths of the major (a) and minor (b) axes of the ellipse according to the relationship: $e=(a^2-b^2)^{1/2}/a$. Curvature (related to instantaneous values of the geocentric distance) is a function of the changing values of the radius vector directed toward the Moon from this same geocentric position (see fig. 24).

In this same connection, it is also important to note that the actual curvature of the orbit is expressed conversely by the term "radius of curvature." A large radius of curvature implies a relatively flat orbital curve, and a small radius of curvature indicates a more sharply curved section of the orbit.

Finally, in the following comparisons, it will be noted that neither the points of maximum *change* in the hourly parallaxes, nor the times of convergence of those values on 0.0″, necessarily agree with the exact times of occurrence of the above-designated orbital positions—or with the mean times of their various combinations. Rather, by nature, they must coincide with the exact times of the greatest or least distance of the Moon from the Earth, whereas the positions specified may or may not do so. Both the theoretically assumed and the actual times are given in the examples which follow, with the data given conforming to the latter circumstance. Allowing for this small exception from idealized lunar motion, the instantaneous curvatures of the lunar orbit at times agreeing quite closely with the particular astronomical conditions enumerated above are discussed in each case. Although the combinations of perigee-syzygy and perigee-quadrature cannot occur within the same lunation, examples chosen from successive lunations closely spaced in time have been used for purposes of comparison. The individual examples are arranged in order of increasing parallax so that the numerical progression in parallax values from apogee-syzygy to perigee-syzygy is clearly evident.

1. Apogee-Syzygy

In this case, because of the position of the Moon at apogee, the distance of the Moon from the Earth is great. Since the eccentricity of the lunar orbit is increased by the coincidence of syzygy with apogee, the lunar distance from the Earth is further increased and the parallax reaches a corresponding very low value.

At this time also, the hourly differences in parallax are decreasing very slowly from already small values toward 0.00″ at minimum parallax, and thereafter increasing by the same small increments. The approximate hourly rate of change around the time of apogee-syzygy in the two examples is only about −3″ per lunar day.

In terms of the changing value of the lunar distance with time which defines the instantaneous figure of the lunar orbit, this very small change over an extended period results in a section of the orbit having a comparatively small curvature and at maximum distances from the Earth.

Examples

Date		Phase	Variation in $\Delta\pi$	Approx. Value of π at $\Delta\pi=0$	Approx. Value of $\Delta\pi$ Per Tidal Day
Of Mean A-S	Of Zero $\Delta\pi$				
1973 Dec. 25.3	Dec. 25.9	NM	(−) to 0.0 to (+)	53′56.50″	−2.94″
1974 Jan. 22.7	Jan. 21.9	NM	(−) to 0.0 to (+)	53′56.73″	−3.30″

2. Apogee-Quadrature

Under this circumstance, the apogee position in orbit is as far removed as is physically possible from any influence of syzygy. In consequence, the resultant configuration represents a modified condition of apogee in which the lunar orbit is perturbed by the Sun exerting its gravitational force at right angles to the line of apsides. The extension of the lunar orbit along this latter axis which occurred at apogee-syzygy is not present and, after passing through apogee-quadrature, the parallax is increased slightly as the Moon, moving toward new or full moon, is deflected toward the Earth by the normal component of the Sun's gravitational force.

The hourly differences in the parallax values decrease numerically through very small negative values toward 0.0″ near apogee-quadrature, and thereafter increase positively at the same slow rate. The result of this astronomical alignment in terms of the instantaneous figure of the lunar orbit is an ellipse of somewhat smaller eccentricity than that associated with apogee-syzygy. The configuration produced is also one of very slightly increased local curvature at apogee-quadrature, in which position the average change in lunar parallax has increased to approximately —5.6″ per lunar day.

Examples

Date		Phase	Variation in $\Delta\pi$	Approx. Value of π at $\Delta\pi=0$	Approx. Value of $\Delta\pi$ Per Tidal Day
Of Mean A-Q	Of Zero $\Delta\pi$				
1974 Oct. 23.8	Oct. 24.5	FQ	(−) to 0.0 to (+)	54′12.90″	−5.70″
1974 Nov. 21.6	Nov. 21.3	FQ	(−) to 0.0 to (+)	54′13.12″	−5.57″

3. Ordinary Syzygy

This represents an orbital situation in which the position of syzygy is located as far as possible from either perigee or apogee—i.e., it involves a syzygy that occurs in the same lunation in which perigee coincides with quadrature.

Under this condition, the lunar parallaxes are increasing rapidly as the result of relatively large values of the hourly differences. The rate of change (second difference) is itself slowly increasing numerically (either positively or negatively) toward a maximum value of the hourly difference at the time of syzygy. Upon reaching this maximum, the hourly rate of change holds constant for some hours, and then declines as slowly as it increased.

In consequence of the rather large values of the hourly differences in parallax, both the parallax and the curvature of the orbit change considerably. The effect of the small value of the second difference is to extend this steady increase in parallax over a longer period of time. Throughout this period, the hourly increase in parallax is cumulative, building to a difference of slightly more than 0.5′ per tidal day in the following typical cases.

Examples

Date		Phase	Max. $\Delta\pi$	Approx. Value of π at $\Delta\pi$=max.	Approx. Value of $\Delta\pi$ Per Tidal Day
Of Mean S	Of Max. $\Delta\pi$				
1974 Oct. 31.0	Oct. 30.3	FM	+1. 44″	56′21. 03″	+35. 50″
1974 Nov. 14.0	Nov. 15.5	NM	−1. 60″	56′39. 16″	−39. 29″

4. Ordinary Quadrature

This configuration is one in which the position of quadrature is located at a maximum separation from either perigee or apogee—i.e., the quadrature occurs in the same lunation in which perigee coincides with either new moon or full moon.

When quadrature is so positioned, the hourly differences in lunar parallax attain their maximum values (increasing positively toward first quarter moon and negatively toward last quarter moon) and thereafter decrease numerically, but carry the same algebraic sign. As they approach and pass their respective maxima, the hourly differences themselves are subject to change at the slowest rate of growth or decline encountered among any of the examples considered, thus maintaining a nearly constant, large increment or decrement.

This implies that the parallax is continuously increasing (and the lunar distances are decreasing—or vice versa) for a considerable period prior to quadrature, resulting in a sizable cumulative change. Because of the large hourly differences, the increase in parallax amounts to nearly 1′ per lunar day in the present examples. The accompanying orbital configuration will be one possessing both sharper curvature and greater instantaneous parallax than are present in the previous cases.

Examples

Date: Of Mean Q	Date: Of Max. $\Delta\pi$	Phase	Max. $\Delta\pi$	Approx. Value of π at $\Delta\pi$=max.	Approx. Value of $\Delta\pi$ Per Tidal Day
1974 Jan. 1.8	Jan. 3.8	FQ	+2. 42″	58′33. 96″	+59. 76″
1974 Jan. 15.3	Jan. 13.2	LQ	−2. 44″	56′38. 62″	−56. 07″

5. Perigee-Quadrature

In this instance, the position of lunar quadrature is subject to the added influence of perigee. The existing small values of hourly difference in parallax decrease numerically only slowly—converging on 0.0″ as the Moon approaches this combined alignment—rather than increase as in the case of ordinary quadrature. In consequence, the lunar parallax—itself at relatively high values—remains nearly constant at these values and changes far less rapidly than in the case of ordinary quadrature. The resulting period of time over which the effect of the greater parallax is felt is proportionately extended.

In addition to the fact that the parallax values are higher than at ordinary quadrature because of its coincidence with perigee, the rate of decline (as well as ensuing growth) of these values proceeds at an average rate (in the examples represented) of only about 3.0″ per lunar day. This results in a prolongation of the relatively high values of the parallax, and a longer lasting, close-to-minimum distance of the Moon from the Earth. The curvature of the lunar orbit is, simultaneously, appreciably flattened.

Examples

Date: Of Mean P-Q	Date: Of Zero $\Delta\pi$	Phase	Variation in $\Delta\pi$	Approx. Value of π at $\Delta\pi$=0	Approx. Value of $\Delta\pi$ Per Tidal Day
1974 Nov. 7.7	Nov. 8.2	LQ	(+) to 0. 0 to (−)	59′16. 20″	+2. 50″
1974 Apr. 28.5	Apr. 27.7	FQ	(+) to 0. 0 to (−)	59′22. 24″	+3. 42″

6. Perigee-Syzygy

Subject to this combined effect, the gravitational forces on the lunar orbit caused by the Moon being in direct alignment with the Earth and Sun at syzygy are further reinforced by the Moon being simultaneously at perigee. Other complex changes in the figure of the lunar orbit which must be considered in this connection are: (1) the tangential component of the Sun's disturbing force on the Moon (a) *increases* the eccentricity of the lunar orbit as the Moon moves from a point halfway between apogee and perigee through perigee to a point halfway between perigee and apogee [f]; and (b) *decreases* the eccentricity as the Moon passes through apogee in the remaining half of the orbit; also (2) the normal component of the Sun's disturbing force (a) *decreases* the lunar orbital eccentricity as the Moon revolves from apogee to perigee; and (b) *increases* the eccentricity during the Moon's motion from perigee to apogee; while (3) the tangential component of the Sun's disturbing force acts to increase the major axis of the lunar orbit at any position of the Moon. As seen from the equation for tangential force in part II, chapter 4, this factor is the most effective when the orbital velocity of the Moon is the greatest, at the position of lunar perigee.

In addition, the gravitational influences are reinforced by an extension of the period of time the Moon remains near an extreme minimum, gravitationally enhancing approach to the Earth at perigee-syzygy. The unusually small lunar distances from the Earth are created a considerable time before perigee and last for an equal time afterward. These distances, as represented (inversely)

[f] *Supplementary Note:* A summary table of the perturbational effects of the normal, orthogonal, and tangential components of the disturbing force is given on page 332 of F. R. Moulton's *An Introduction to Celestial Mechanics* (2d rev. ed., 1914). However, the influence of the tangential force on eccentricity during successive intervals in the lunar orbit as tallied is just backward in comparison with the mathematical analysis on page 328 of this same work.

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by the lunar parallax, characteristically decrease quite slowly as the Moon approaches its perigee-syzygy position. At perigee-syzygy, the very large values of the parallax do, in fact, actually change at a very slightly faster rate than the corresponding low values at the opposite extremity in orbit, lunar apogee. The maximum parallaxes (and minimum lunar distances) at perigee-syzygy also last a slightly shorter period of time at their extreme values than do the minimum parallaxes and maximum lunar distances at the previously discussed apogee-syzygy position. (Cf., top and bottom solid curves in both figs. 37 and 38.)

However, approaching perigee-syzygy, both the increase to the maximum parallax and the amount of change in these extreme maximum values of the parallax proceed at very much slower rates than the change in parallax at either ordinary syzygy or ordinary quadrature. The average changes in the lunar parallax in these three separate cases are approximately 11″, 37″, and 58″ per lunar day, respectively. And, of course, the value of the parallax itself in the case of perigee-syzygy is greater than that in all of the preceding examples.

Accordingly, the resulting instantaneous orbital configuration is one in which, while the Moon is at a position of nearly closest possible approach to the Earth in its orbit, the curvature of the orbit is also the smallest possible. A corresponding increase in the duration of the near-maximum tidal forces produced by the Moon's extreme proximity to the Earth occurs.

Examples

Date		Phase	Variation in $\Delta\pi$	Approx. Value of π at $\Delta\pi=0$	Approx. Value of $\Delta\pi$ Per Tidal Day
Of Mean P-S	Of Zero $\Delta\pi$				
1974 Jan. 8.5	Jan. 8.5	FM	(+) to 0. 0 to (−)	61′30. 01″	+11. 64″
1973 Dec. 10.5	Dec. 10.9	FM	(+) to 0. 0 to (−)	61′14. 43″	+10. 96″

The detailed representation of four contrastingly different curves of parallax, representative of cases 1, 2, 5, and 6, above, plotted for appropriate positions in the lunar orbit, will now be analyzed.

A Quantitative Comparison of the Lunar Parallax at Times of Perigee and Apogee

If successive equatorial horizontal parallax values representing the Moon's changing distance from the Earth are plotted against the time (expressed in terms of lunar longitude in orbit) and the true elongation of the Moon with respect to the Sun, for a period on either side of perigee-syzygy, the curve peaks represented in the upper left and central portions of figs. 37 and 38 result.

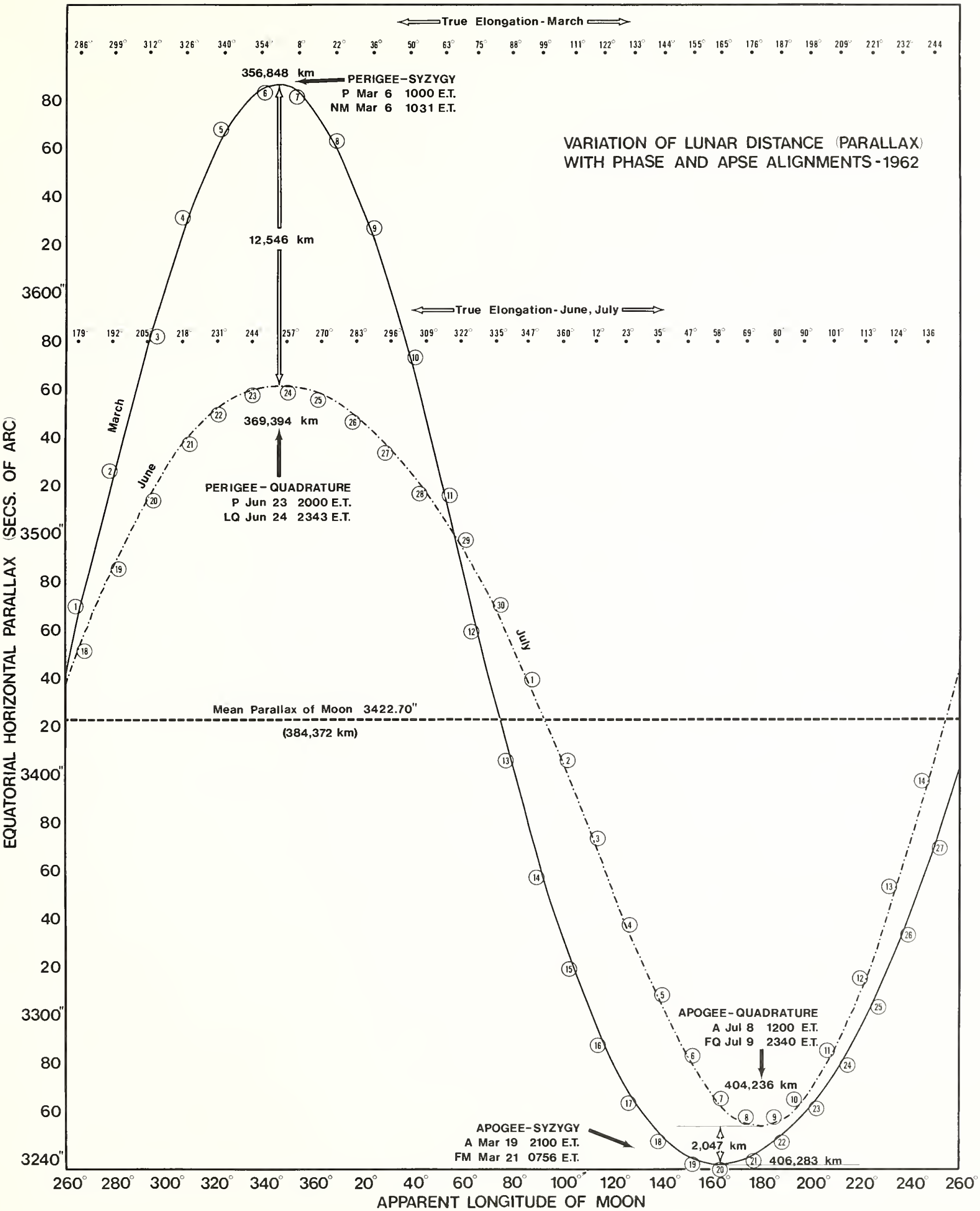
In these graphs, the ordinate values represent the closer proximity of the Moon to the Earth as a function of increasing height (or positive amplitude) of the curve. Alongside each curve are numbers in circles which indicate (from left to right) the passage of time in terms of successive dates of the month. The abscissa axis shows, at the bottom (from left to right), movement of the Moon through increasing longitude from 0° to 360° and then repeating.

Near the top of each chart, along appropriate horizontal axes, true elongations of the Moon from the Sun are indicated as angular values from 0° or 360° at new moon (conjunction), through 90° at first quarter moon, 180° at full moon, and 270° at third quarter moon. It should be brought out in terms of an analytic discussion in the next section that both of these scales represent true (apparent) rather than mean longitude.

The dashed horizontal line shows the relationship of the mean or average horizontal parallax during one lunar year, for all dynamic conditions involving the Earth, Moon, and Sun. The center-to-center distances of the Moon from the Earth, in kilometers, corresponding to various significant astronomical alignments and circumstances, are also included.

In fig. 37, the solid curve depicts the decreasing distance of the Moon from the Earth between 1962 March 1 and the Moon's closest approach at the perigee of March 6.43, then through a distance increasing continu-

Figure 37.—This diagram illustrates typical values of the lunar parallax occurring at: (1) the close perigee-syzygy (proxigee-syzygy) alignment of 1962 March 6, greatly contributory to tidal flooding; (2) the immediately following instance of apogee-syzygy; (3) a representative perigee-quadrature; and (4) a case of apogee-quadrature. Figure 38 shows similar comparative examples.


VARIATION OF LUNAR DISTANCE (PARALLAX) WITH PHASE AND APSE ALIGNMENTS-1962
True Elongation - March
True Elongation - June, July
356,848 km
PERIGEE-SYZYGY
P Mar 6 1000 E.T.
NM Mar 6 1031 E.T.
12,546 km
369,394 km
PERIGEE-QUADRATURE
P Jun 23 2000 E.T.
LQ Jun 24 2343 E.T.
Mean Parallax of Moon 3422.70"
(384,372 km)
APOGEE-QUADRATURE
A Jul 8 1200 E.T.
FQ Jul 9 2340 E.T.
404,236 km
2,047 km
406,283 km
APOGEE-SYZYGY
A Mar 19 2100 E.T.
FM Mar 21 0756 E.T.
March
June
July
EQUATORIAL HORIZONTAL PARALLAX (SECS. OF ARC)
APPARENT LONGITUDE OF MOON

ously to the position of apogee on March 19.88 and, thereafter, diminishing again toward the next perigee on April 3.88.

Certain comments are in order in connection with these graphs:

1. The mean epoch of perigee-syzygy in fig. 37 is 1962 March 6 1015.5^h or March 6.4274 (e.t.). On the scale of these graphs, the values of π are plotted by half-day intervals only. Rounding off to the nearest half-day, the ephemeris value for π on March 6.5 is $61'2.6702'' = 3{,}686.702''$. Again, in figs. 37–38, one second of arc is the smallest unit plotted. In the interpretative discussion given here and immediately following, seven significant figures will be retained and finally rounded back to six only to demonstrate the sensitivity of $0.001''$ in parallax. Other practical considerations obviously preclude an accuracy given to the nearest mile in the results.

The formula for converting parallax angles to linear distance is

$R = 206{,}264.8'' r/s''$, where

R = the center-to-center distance between the Earth and the Moon, in kilometers or miles

r = the equatorial radius of the Earth in the same units (6,378.160 km = 3,963.205 mi)

s = the geocentric parallax of the Moon, equal to the arc, in seconds, subtended at the distance of Moon by the Earth's equatorial radius

Thus, the lunar parallax at this approximate perigee-syzygy position of 1962 March 6.5 corresponds to a distance of 356,848 km (221,735 mi) between the center of the Moon and the center of the Earth.

Lunar *apogee* (or *exogee,* in a later definition of the term) is attained at 2100 e.t. on March 19. Calculated as before from the parallax ($\pi = 53'58.102''$) for the nearest half-day, 1962 March 20.0 (where the sign of $\Delta\pi$ also is changing appropriately), the Moon at this time recedes to a distance of 406,283 km (252,453 mi) from the Earth. This is an increase in distance of 49,435 km (30,717 mi) over the distance at perigee-syzygy. Since the tide-raising force varies inversely as the cube of the distance, a sizable additional force component is available at perigee-syzygy compared with apogee-syzygy.

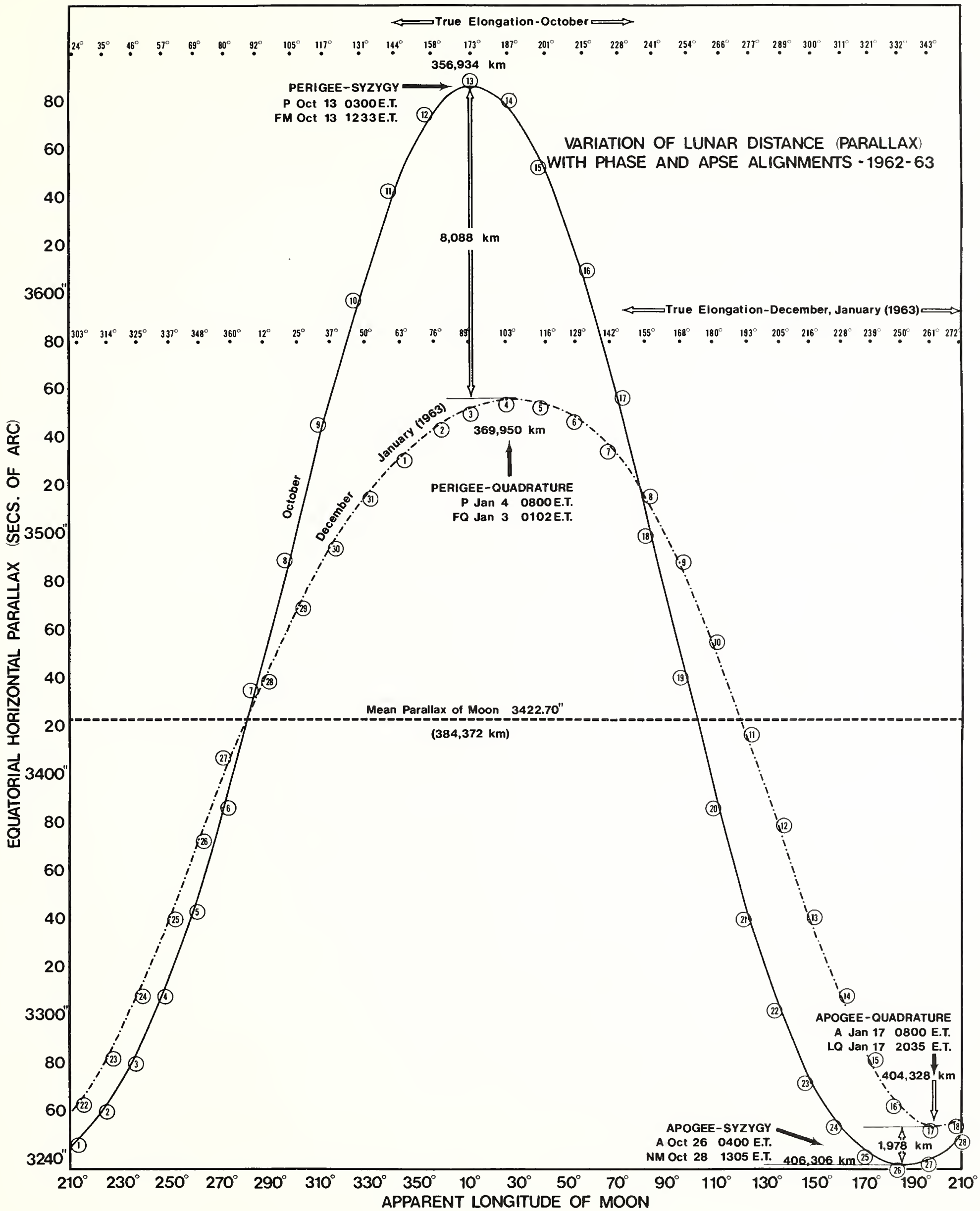
2. A second pair of curves, consisting of alternate dots and dashes, has been plotted with reference to the same abscissa and ordinate systems, but with different appropriate dates to show the change in parallax values occurring between successive conditions of perigee-quadrature and apogee-quadrature. The first set of curves (fig. 37) corresponds to times in June and July 1962 when the Moon at last quarter and first quarter was in a position very close to (although not precisely in agreement with) perigee and apogee, respectively. (In these various analyses, it is important to note a technical distinction: the *date* of perigee implies that the Moon actually occupies its closest monthly position to the Earth; the *position* of perigee does not necessarily imply that the Moon is actually at this location in its orbit.) At times of perigee-quadrature and apogee-quadrature, the gravitational force of the Sun acting upon the Earth is directed at right angles to the force of the Moon exerted on the Earth, and the Moon's tide-raising action is considerably reduced.

In the January 1962 positions of perigee-quadrature (fig. 38), the first quarter moon very nearly coincides with the position of perigee, while the third quarter moon is closely aligned with the position of apogee. Again, as in the first example, a line drawn from the Moon to the Sun is at 90° to the line of apsides connecting perigee and apogee.

In accordance with both the lunar evection and lunar variation effects on parallax outlined in chapter 4, when the line of apsides coincides with quadratures, parallax is affected the least. The amplitudes of both the peak and trough of the curve (fig. 37) are reduced (to parallaxes corresponding to distances of 369,394 km or 229,531 mi and 404,236 km or 251,181 mi, respectively). In this example, the greatest observed difference in the distance of the Moon resulting from such syzygy-quadrature variations in parallax occurs between the mean perigee-syzygy of March 6.43 and the mean perigee-quadrature of June 24.41, and is 12,546 km or 7,796 mi. A much smaller variation in distance (2,047 km or 1,272 mi) occurs between the mean apogee-syzygy of March 20.60 and the mean apogee-quadrature of July 9.24.

Similar relationships are shown in figure 38 in the comparison of the mean perigee-syzygy of October 13.32 with the mean perigee-quadrature of January 3.69, and the mean apogee-syzygy of October 27.86 with the mean apogee-quadrature of January 17.60.

FIGURE 38.—The interpretation of these curves and those of figure 37 is contained in the text. The value of the mean lunar parallax indicated (3422.70″) is that published in *Explanatory Supplement to the Astronomical Ephemeris and The American Ephemeris and Nautical Almanac* (1961) pp. 26s, 27s, just prior to the case examples indicated. This value was subsequently announced to be a misprint. The corrected value as it appears in *Supplement to the A.E.,* 1968 (1966) pp. 20s, 26s, is 3422.608″. The slight difference is, however, in this instance negligible.



True Elongation-October
356,934 km
PERIGEE-SYZYGY
P Oct 13 0300 E.T.
FM Oct 13 1233 E.T.
VARIATION OF LUNAR DISTANCE (PARALLAX) WITH PHASE AND APSE ALIGNMENTS - 1962-63
8,088 km
True Elongation-December, January (1963)
369,950 km
PERIGEE-QUADRATURE
P Jan 4 0800 E.T.
FQ Jan 3 0102 E.T.
January (1963)
October
December
Mean Parallax of Moon 3422.70"
(384,372 km)
APOGEE-QUADRATURE
A Jan 17 0800 E.T.
LQ Jan 17 2035 E.T.
404,328 km
APOGEE-SYZYGY
A Oct 26 0400 E.T.
NM Oct 28 1305 E.T.
406,306 km
1,978 km
EQUATORIAL HORIZONTAL PARALLAX (SECS. OF ARC)
APPARENT LONGITUDE OF MOON

3. Most distinctive of the relationships between the several curves, however, are the much steeper slopes and narrower and sharper crests shown for the perigee-syzygy dates compared with the corresponding perigee-quadrature, apogee-quadrature, or apogee-syzygy dates.

Significantly, the period of time required to cover approximately 180° of celestial longitude centered around perigee in the first two cases is approximately the same, 12 days. Yet, on each day of the 12-day period from 1962 March 1 to March 13, the Moon has moved a far greater distance toward the Earth (indicated by the steepness of the curve's slope) than in the 12-day period 1962 June 18 to June 30. Because of this considerably greater "in-and-out" motion with respect to the Earth (substantiated by the fact that radial components along the line-of-sight do no produce any apparent change in longitude), the Moon's orbital motion must also be far swifter at this time to cover the same angular distance across the sky in the same period of time. The sharper peak of the curve at the time of perigee-syzygy thus also graphically demonstrates the dynamically imposed circumstance of greater angular speed of the Moon at this time resulting from the parallactic inequality, and the need of an increased catch-up interval by the rotating Earth (see pt. II, ch. 6).

Conversely, the more rounded crest on the perigee-quadrature curve indicates a smaller radial component of motion as well as a smaller orbital velocity. The effect is also very evident in comparing the rounded peak of the curve depicting the Moon's approach to *apogee*-syzygy and the much sharper peak associated with *perigee*-syzygy.

(It must be carefully noted that the *daily differences* in parallax quoted in the discussion of local orbital curvature in the preceding section represent corresponding changes in lunar distance over a very small portion at the extreme peaks of the present curves. The curves of figures 37, 38 represent the *change* in the parallax, while their geometric slopes denote the *rate of change* of the parallax, over periods of an entire week before and after perigee. Different conditions of curvature of the lunar orbit obviously will result from the eight configurations represented.)

Causes of Variation in the Shape of the Lunar Orbit and in the Consequent Tide-Raising Forces

In either of the two cases, full moon at perigee or new moon at perigee, the Sun's gravitational force reinforces that of the Moon and acts to raise increased (spring) tides as a result of the syzygy alignment. It will shortly be graphically demonstrated (figs. 153–163) that, because of the Moon's closer approach to the Earth at perigee, considerably higher tides occur at perigee-syzygy than at apogee-syzygy. A cogent preliminary question is, why are some perigean spring tides higher than others?

Effects of the Individual Syzygies

In this respect, it is first necessary to note (figs. 39–40) the important distinction that the gravitational attraction of the Sun upon the Moon when it is at full moon is not the same as when it is at new moon. This difference in the force attraction of the Sun upon the Moon as exerted at conjunction and at opposition can have a perceptible effect on: (1) the lunar evection term and the Moon's resulting proximity to the Earth (i.e., the lunar parallax); (2) the corresponding tidal forces acting on the Earth; and (3) the orbital velocity of the Moon in crossing the nearly common line of apsides and syzygies (here assumed to be coincident, although such a precisely commensurable relationship is practically impossible of attainment in nature).

The mass of the Sun is 333,432 times that of the Earth, and the Sun's gravitational force (disregarding its greater distance from the Earth) is proportionately larger than that of the Moon. However, because of the much closer distance of the Moon from the Earth compared with the Sun-Earth distance, the gravitational force of the Earth on the Moon will always be greater than, and override that of the Sun. The basic eccentric configuration of the Moon's orbit and the location of the perigee and apogee positions are, nevertheless, subject to the altering and perturbing influence of the Sun's gravitational attraction.

1. Case One: Full Moon at Perigee

When full moon occurs nearly coincidentally with perigee (fig. 39), the Sun's evectional perturbing force is exerted directly along the same axis representing the Earth's gravitational force on the Moon. The result of these combined gravitational forces of Sun and Earth is to deflect the Moon earthward toward a position interior to that which would be the case subject to the Earth's gravitational force alone. In the case of a full moon occurring almost exactly at perigee, the forces of the Sun and Earth act together in the same direction and the amount of inward deflection of the Moon, subject to the full resultant force (EM+SM), reaches a maximum. Thus, for increasingly closer perigee-syzygy alignments, the Moon comes correspondingly closer to the Earth. The lunar parallax increases accordingly.

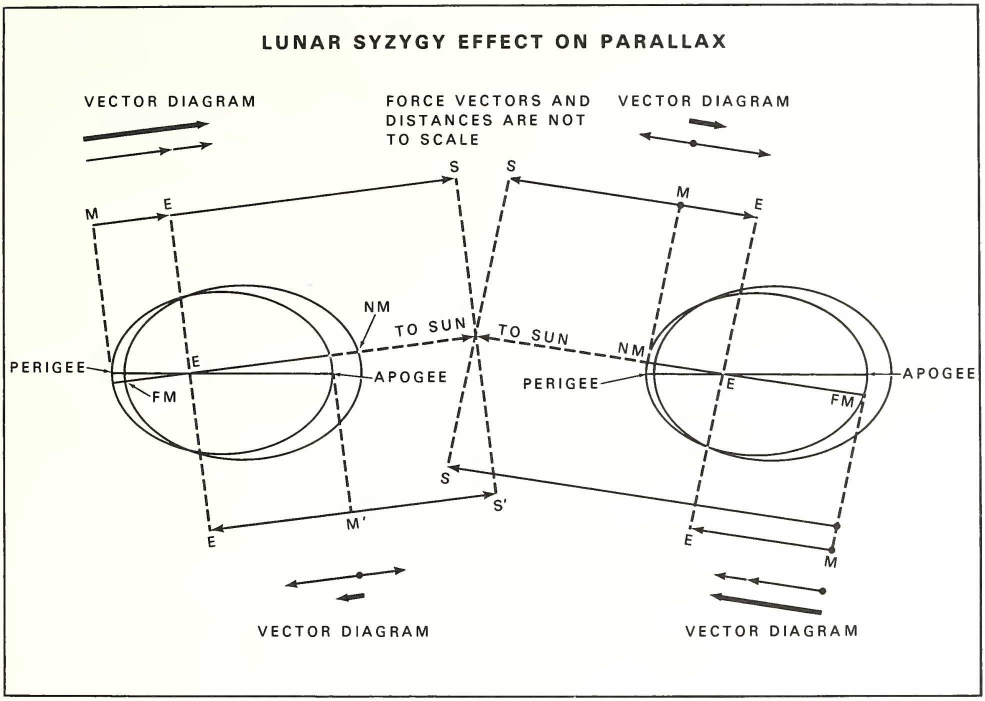


Figure 39.—The lunar orbital perturbing effect which exists when a perigee-syzygy alignment occurs at *full moon.* The reinforcing gravitational attractions of the Sun and Earth together result in a greater parallax than if their attractions on the Moon are opposing, as is the case when perigee-syzygy coincides with new moon.

Figure 40.—The corresponding situation with all other factors unchanged, but with perigee-syzygy occurring at *new moon.* The gravitational attraction of the Sun upon the Moon is then subtracted from the pull of the Earth on the Moon. The resultant perturbational displacement of the Moon toward the Earth is not as great as in figure 39.

As the Moon revolves from perigee-syzygy (FM) to the next succeeding apogee-syzygy (NM), it moves additionally outward in orbit as the Earth's gravitational attraction for the lunar body is reduced by that of the Sun exerted in the opposite direction. Because of the much smaller Earth-Moon distance compared with the Sun-Moon distance, the Earth's gravitational force on the Moon is larger than that of the Sun and remains in control of the Moon's orbital revolution. The lunar apogee position is established solely by the Moon's elliptical motion in the two-body Earth-Moon system. However, this configuration of new moon-apogee in which the Moon is farthest from the Earth also means that it is simultaneously in a closer position to the Sun than at full moon, and closer to the Sun than the Earth is. The Sun's force on the Moon, directly opposed to that of the Earth and reduced thereby (SM′—EM′), still acts to increase the apogee distance by a sensibly greater amount, and a maximum apogee distance is reached at the new moon immediately preceding or following the full moon which occurs at perigee. Oppositely stated, the net or resultant centripetal force vector obtained by subtracting the Sun's gravitational force from that of the Earth on the Moon is reduced, and the Moon moves outward toward a greater distance from the Earth.

The lunar orbit acquires a larger eccentricity *e* (see pt. II, ch. 4), which has the same effect along the line of apsides as if the entire orbit were shifted toward the Sun in fig. 39.

2. Case Two: New Moon at Perigee

Now consider the situation where the new moon is at perigee and the full moon at apogee (fig. 40). The Moon is closer to the Sun at this NM-perigee position than it is at FM-apogee. The gravitational attraction of the Sun upon the new moon, although greater than in the FM-perigee example, is now oppositely directed to the force of the Earth on the Moon and must be subtracted therefrom. In terms of the net force EM–SM, because the Sun's force on the Moon is larger than in case 1, as well as being opposed to that of the Earth, the resultant centripetal force is smaller, and perigee distance is not reduced as much.

Likewise, at the apogee position which is, in this second (FM) case, more distant from the Sun than in the first (NM) case, the Sun's perturbing force is weaker than before. The Earth is, however, now located closer to the Sun than the Moon is, and is gravitationally displaced from the Moon toward the Sun, increasing the distance between Earth and Moon. Thus, the apogee position is again moved to a relatively greater separation from the Earth, but not as much so as in the NM-apogee case. In figs. 39–40, the Moon's orbit is effectively displaced to the right with respect to the Earth in the first case, and to the right (although not as much) in the second case.

For the foregoing reasons, the highest values of the lunar parallax are all found in the combination of full moon and proxigee-syzygy in table 13. As described in the second following section, when the Moon is near solar perigee, these influences are further enhanced.

In recapitulation, it is clear that, among the various factors contributing to a closer proximity of the Moon to the Earth at perigee-syzygy, the initial cause is the change in eccentricity e of the lunar orbit resulting from evection. The solar gravitational influence acts as an additive force, increasing the eccentricity of the lunar orbit as the Moon approaches the position of perigee. The sequence of events is: (1) passage of the Sun across the lunar line of apsides at either upper or lower apse—a necessary accompaniment of a perigee-syzygy alignment; (2) an increase in e with the Moon at perigee-syzygy, produced by the solar tangential force (whose effect on e ranges from zero to a maximum influence to zero again between the two intersections of the force vector and the minor axis of the lunar orbit) with a corresponding decrease in e as the Moon nears apogee-syzygy; these effects are accompanied by a decrease in e as the Moon moves between apogee and perigee, produced by the normal force of the Sun's gravitational attraction upon the lunar orbit; (3) a resulting net increase in e at the time of perigee-syzygy; (4) a coincident increase in the semimajor axis a of the Moon's orbit, but to a lesser extent; (5) since the value of the parenthetical term in the equation $q=a(1-e)$ thus decreases at a faster rate than a increases, the value of q, the perigee distance, must also diminish at perigee-syzygy; (6) as q grows smaller, the orbital velocity V of the Moon must increase at this time in accordance with Kepler's third law.

The consequent catch-up effects responsible for lengthening the lunar day and month will be described in the following chapter.

A numerical example showing the actual *computed* values of the eccentricity and semimajor axis of the lunar orbit at a time of extremely close perigee-syzygy (proxigee-syzygy) as compared with the *mean* values of these same quantities will best serve to confirm the previous statements. The determination of these two elements of the lunar orbit would ordinarily pose all of the difficulties of a three-body problem where the Moon, as here, is subject to the strong perturbational action of the Sun. However, where the Moon's instantaneous position in orbit already has been computed from lunar theory, using the appropriate equations of disturbed motion, it is possible to reverse the computational process and determine the instantaneous values of these elements.

The equations for a conic section given in a succeeding paragraph apply, in general, only to a Keplerian ellipse completely free from external or internal disturbing forces. Alternately, they are applicable in a so-called osculating orbit at the position (or instant) of osculation selected for computational purposes where the actual, or perturbed, and the theoretical, or unperturbed, orbits coincide. The particular orientation of the Sun, Earth, and Moon along, or very close to, the extended lunar line of apsides corresponding to a time of perigee-syzygy provides just such a case lending itself to analysis using the special properties of an osculating orbit.

In methods of three-body or disturbed orbit computation, it is customary to choose as the initial osculating position, in both the perturbed and unperturbed orbits, the position of perihelion—or, in the case of the Moon, the matching counterpart is perigee. Thus, the instant of $t=0$, the *epoch of osculation,* becomes the position of perigee, and the orbital element T specifies the date and time when the Moon is at perigee. Subject to close perigee-syzygy conditions, this time is also within less than an hour to a few hours of the instant of alignment of Earth, Moon, and Sun at syzygy.

The circumstance of perigee-syzygy therefore provides a singular opportunity to study the effect of perturbations on the lunar orbit in their least complicated form. The lunar *evection* is the perturbation most effective in increasing the values of both the eccentricity and semimajor axis of the lunar orbit at this time. Its effects will now be quantitatively evaluated by the use of computed data in *The American Ephemeris and Nautical Almanac.*

Where:

- v = the *true anomaly*, or angular distance of the Moon from perigee
- p = the *latus rectum* of the Moon's elliptical orbit, equivalent to the radius vector (ρ) for $v=90°$
- q = the *perigee* distance, or least monthly distance between the Moon and the Earth
- e = the *eccentricity* of the lunar orbit
- ρ = the *radius vector*, or distance of the Moon from the Earth at any instantaneous position in orbit

Then:

$$p=q(1+e)=\rho(\text{at } v=90°)$$

$$q=a(1-e)=\rho(\text{at } v=0°)$$

In a perturbed orbit, each of these equations is theoretically valid only for the moment of arbitrarily selected zero-disturbance in the osculating orbit—equivalent in this case to the instant of perigee-syzygy as above described. However, as noted several paragraphs earlier, the values of both the celestial longitude (λ) and the radius vector (ρ) of the Moon tabulated in *The American Ephemeris and Nautical Almanac* contain the effects of perturbations and are, therefore, representative of the perturbed orbit. By definition, the value of p—the only quantity not evaluated for the time of perigee-syzygy—is equal to the tabulated value of ρ for the position where $v=90°$. Hence, the time corresponding to this position in the lunar orbit 90° from perigee can be obtained by reverse interpolation in the tables for the instant where $v=90°$.

The true anomaly is the angular distance of the Moon, expressed as a difference in longitude, from perigee. The true longitude of perigee is, in turn, equal to its instantaneous angular distance from the vernal equinox. At a close perigee-syzygy, the Moon itself must also be at very nearly this same longitude. The true longitude of perigee may thus be obtained, to a close approximation, by extracting the apparent longitude of the Moon from *The American Ephemeris and Nautical Almanac* for the exact time of perigee, also tabulated. An alternate procedure is to interpolate the value of the mean longitude of perigee from various available tables. (At the time of perigee-syzygy, the mean longitude and true longitude of the Moon are theoretically the same.) However, because the instant of the Moon's passing through perigee is being considered, the accelerated motion of perigee at the time of perigee-syzygy is not taken into account in the mean motion of the line of apsides, and hence in the mean longitude of perigee. The resulting differences are shown among the following computations.

If 90° is added to the derived true longitude of perigee, the true longitude of the Moon at the position p is obtained. This longitude of the Moon as it reaches the latus rectum of the orbit (subject to the perturbed motion imposed in the interim since perigee) can then be used—again by a process of reverse interpolation in the ephemeris—to find the time at which the Moon reaches this position.

Proceeding next to the table of true geocentric distance of the Moon published in the ephemeris, this interpolated time can be used to find the actual value of ρ, the radius vector of the Moon, at this position in orbit. This value corresponds to the dimension of p.

The value for q for the instant of perigee-syzygy also can be obtained from this same table.

Then since:

$$e=\frac{p}{q}-1, \text{ and } a=\frac{q}{(1-e)},$$

substituting the appropriate values and following the procedure outlined above, a comparison can be made between the results obtained for a condition of close perigee-syzygy and the adopted mean values for e and a which represent an average of all conditions encountered in the lunar orbit.

For the close perigee- (proxigee-) syzygy alignment of 1974 Jan. 8.5 (G.c.t.):

(a) The value of the apparent (true) longitude of the Moon interpolated from *The American Ephemeris and Nautical Almanac* for a time corresponding to that of perigee, and therefore very nearly equivalent to the true longitude of perigee is:

$$106.828765°$$

By comparison, a derivation of the approximate *mean* longitudes of the Moon and perigee from tables 4–5 in *Harmonic Analysis and Prediction of Tides* gives:

Mean longitude of the Moon

$$106.95°$$

Mean longitude of perigee

$$106.23°$$

(b) The apparent longitude of the Moon's position at point p is then:

$$106.828765°+90.000000°=196.828765°$$

Whence, using inverse interpolation in the ephemeris to obtain the time at which the Moon reaches p:

$$t_p=\text{Jan. } 14.6866$$

(c) The value of ρ, and hence the corresponding value of p at this time, obtained by the use of polynomial coefficients in the table of true geocentric distances of the Moon is:

$$\rho=p=60.160203 \text{ Earth-radii}$$

(d) Similarly obtained, the value of q at the perigee of 1974 Jan. 8.4583 is:

$$\rho=q=55.9010709 \text{ Earth-radii}$$

Then:

$$e_q=\frac{p}{q}-1=0.076005$$

(e) Comparing this with the mean value of the eccentricity of the lunar orbit:

$$\bar{e}=0.05490$$

the value of the eccentricity at the time of a very close perigee-syzygy alignment thus represents an increase of 38.4 percent above the mean value of the eccentricity. (In the classic work, *Astronomy*–

Vol. I, by Russell, Dugan, and Stewart, the authors specify that when the Sun crosses the line of apsides of the lunar orbit, the resulting increase in eccentricity is about 20 percent. This value, however, refers to the average of all cases, including both wide separations between perigee and syzygy at the time of solar coincidence with the line of apsides, and the special case of a close perigee-syzygy, as here exemplified.

(f) Also:

$$a = \frac{q}{1-e} = 60.509753 \text{ Earth-radii}$$

By comparison, at the Earth's mean distance and eccentricity, the mean semidiameter of the lunar orbit is:

$$\bar{a} = \frac{239{,}000 \text{ mi}}{3{,}963.2 \text{ mi}} = 60.304804 \text{ Earth-radii}$$

The lengthening of the semimajor axis of the Moon's orbit at the time of such a close perigee-syzygy alignment thus represents an increase of only 0.3 percent with respect to its mean value. This comparatively small increase in the semimajor axis over its mean value, when compared with the much larger increase in the eccentricity of the orbit at this same time, accounts for the fact that the distance of the Moon from the Earth at perigee as given by the equation

$$q = a(1-e)$$

also consistently decreases at the time of a close perigee-syzygy alignment.

The Effect of Solar Perigee

In table 13, a very noticeable consistency appears in the fact that, over a 400-year period, the largest values of lunar parallax tabulated all occur in the winter months of the year, between October 31 and March 8. This circumstance immediately suggests the effect of the Sun's additional gravitational force (the solar inequality) on the Moon at the closer distance of solar perigee, a phenomenon which occurs near to the Earth's perihelion position. Because of the proximity of the Sun to the Moon during this circumstance, the extra solar force acting adds its effects to those noted above. By further increasing the instantaneous eccentricity more than the semimajor axis of the lunar orbit in accordance with the previously described conditions, this supplemental force also increases the lunar parallax. At the same time, as will be seen in chapter 6, it slightly diminishes the orbital velocity of the Moon at perigee-syzygy by reducing the Earth's pull on the Moon.

The Effect of Coplanar Lunisolar Declinations

Another significant relationship evident from table 13 is the fact that, in each of these closest approaches of the Moon to the Earth, the lunar declination has a positive sign. Combined with the circumstance that all of these cases of maximum lunar parallax occur (near perihelion) in the winter months when the Sun is south of the Equator and, therefore, always at a minus declination, the conclusion is obvious. At these times of close proxigee-syzygy alignment and large values of parallax, not only are the Sun, Earth, and Moon at full phase aligned nearly exactly in celestial longitude (or right ascension) at a time near perihelion, but they also lie along a straight line passing from the negative declination of the Sun through the center of mass of the Earth to the positive declination of the Moon. The combined gravitational force components of the Sun and Earth, exerted in or very nearly in the declinational plane, greatly enhance the total force potential acting upon the Moon's orbit, serve to increase the eccentricity of this orbit, and aid in augmenting the Moon's parallax at proxigee-syzygy to a near-maximum value. For a further consideration of all elements contributing to the above-cited winter phenomenon of the Northern Hemisphere, see also page 151, "Seasonal Factors Influencing the Production of Heightened Tides."

The three-dimensional alignment of Sun, Earth, and Moon in a common or near-common plane of declination as well as celestial longitude (or right ascension) during these winter months is thus an additional direct cause for the preferential grouping of these tabulated maximum values of π. Significantly, the comparatively high frequency of severe coastal storms accompanied by strong, persistent, onshore winds in these winter months adds a further potential factor for tidal flooding at such times.

The Effect of Nodal Alignment

The alignment of Sun, Earth, and Moon in celestial latitude is of further importance in the same connection. A significant reinforcement in the magnitude of the lunar parallax can occur when the Moon at perigee-syzygy is simultaneously at one of its two lunar nodes ($\beta = 0°$), while the positions of perigee-syzygy and the lunar node are also in the same celestial longitude.

This condition can come about as the result of a commensurable relationship between the rotation period of the Moon's line of nodes and that of the lunar line of apsides. The former perturbed motion (taking place in a direct, or counterclockwise sense as viewed from the north pole of the Moon's orbit) requires about 18.612

years to complete one rotation; the latter, retrograding in a clockwise sense, requires approximately 8.849 years. (The units specified are *tropical years* of 365.24219878 mean solar days.)

However, for the effect of nodal alignment to occur simultaneously with both the Moon and the Sun being at their closest distances from the Earth, as well as in mutual alignment in longitude—to yield the ultimate requirement for coincidence of node, apse, and perihelion—is a very rare astronomical circumstance. This is indicated from the fact that, as previously specified, the last previous occurrence was in A.D. 1340.

Summary Evaluation of Extreme Lunar Parallaxes

The two principal astronomical perturbing effects responsible for significant changes in the values of the lunar parallax upon different occasions of perigee-syzygy are (a) lunar evection and (b) lunar variation. The phenomenon of evection acts to increase the eccentricity of the lunar orbit and thereby effectively to bring the Moon closer to the Earth at the position of perigee (see fig. 26A). The lunar variation has a similar result, but involves a different cause in decreasing the Moon's perigee distance from the Earth at times of perigee-syzygy alignment (see fig. 27B).

Because the Sun is closest to the Earth during the Northern Hemisphere winter season, these two influences on the Moon's orbit occur most prominently in the winter months. The closest possible approaches of the Moon to the Earth (with resulting increased tidal forces) occur early in the month of January when the Earth is near its perihelion position (closest annual approach to the Sun), usually around January 2–4.

The generally accepted absolute maximum value of the lunar parallax (derived from Brown's lunar equations as the highest value theoretically possible) is $\varpi_{max.} = 61'32''$ (fig. 41) The corresponding absolute minimum value is $\varpi_{min.} = 53'55''$.

Table 16 represents a computer printout of all perigee-syzygy alignments in which the separation-interval between components is $\leq 24^h$, occurring over the 400-year period between 1600 and 1999. From the special consolidation of these data in table 13, it has been determined that the closest approach[g] of the Moon to the Earth at a time of proxigee-syzygy during this 4-century period occurred on 1912 January 4, at 1300^h G.c.t. (perigee-syzygy separation-interval +6.5 *minutes*). At this time, the full moon approached the Earth within a center-to-center distance of 356,374 km or 221,441 mi. However, this distance can be considerably less for a point on the Earth's surface and directly beneath the Moon (i.e., with the Moon on the meridian of the place and directly in the zenith). For the purpose of determination of any local tides, the effect of the lunar tide-raising action must be considered in terms of the Moon's distance from the Earth's surface at the latitude where the tides under evaluation occur.

In a similar connection, as a result of the lunar augmentation effect (fig. 25A), the Moon is some 4,000 miles (a distance equal to the Earth's semidiameter) closer to the surface of the Earth when the satellite is in the zenith than when it is just rising or setting on the horizon. The Moon's actual distance from the Earth's surface is, accordingly, a function of the latitude of the place, the vertical angular distance (altitude) of the Moon above the horizon, and the lunar declination (or vertical angular distance north or south of the celestial equator). Because of the lunar nodical cycle, the latter value reaches a maximum value every 18.6 years. In the latitude of Atlantic City, N.J., as an example, the theoretically closest possible approach of the Moon to the Earth's surface at this largest possible declination angle of the Moon ($\pm 28°47'$) and with the Moon transiting the meridian, is 350,008 km or 217,485 mi.

[g] *Note:* The parallaxes listed in this table are expressed for the times of perigee and syzygy, which may be uncertain by several hours. Because of the difference between topocentric and equatorial geocentric horizontal parallax, on some occasions the lunar distance from a position on the surface of the Earth located at high latitudes and with the Moon at a large meridian altitude may be even less than at the precise time of perigee- or proxigee-syzygy, as was the case for 1974 January 8.5 (G.c.t.).

See footnote (c) in this same chapter for a further discussion of the 1912 January 4 instance of proxigee-syzygy in terms of the lack of associated tidal flooding.

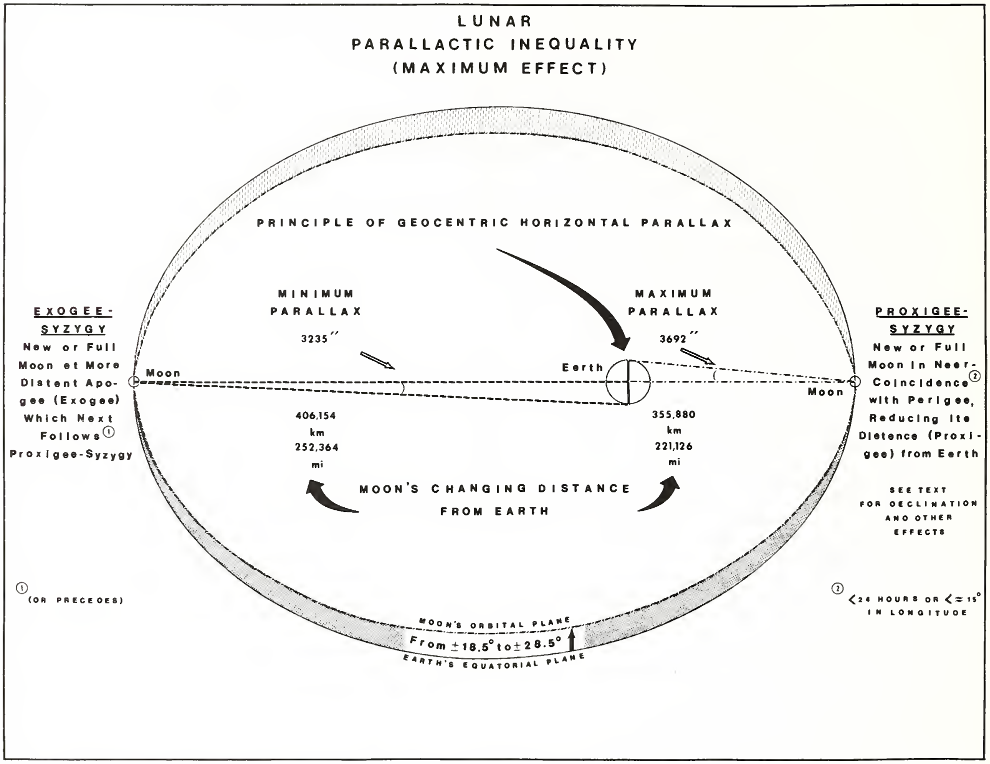


FIGURE 41.—A graphic representation showing that the geocentric equatorial horizontal parallax is equal to the angle subtended by the equatorial semidiameter of the Earth's figure as seen from the instantaneous distance of the Moon. The maximum value of the lunar parallax here indicated (61′32″ ±1″) is that derived in a computerized evaluation of this term at the U.S. Naval Observatory in 1976.

Table 16

Cases of Perigee- (Proxigee-) Syzygy

$P-S = \leq 24^h$

1600–1999

Introduction to Table 16

The computer printout of table 16 was provided by Dr. Thomas C. Van Flandern, of the Nautical Almanac Office, U.S. Naval Observatory. The mathematical expressions used in deriving the quantities given in this table are listed below. It should be observed that several of these evaluating equations involve two different sets of series expansions.

Certain of the original approximate solutions (whose constituent terms are indicated in table 16A) were found to show minor but unacceptable differences when compared with corresponding data appearing in *The American Ephemeris and Nautical Almanac* over the more than 120 years of its publication. The small residuals (ephemeris value minus computer printout value) appeared especially when the separation-interval between perigee and syzygy was 2 hours or less (i.e., at a time of maximum perturbation of the lunar orbit in the parameters represented by the formulae).

A considerably more refined approach, more than doubling the number of terms defining the quantities most affected, was adopted in the preparation of the final printout. These more precise calculating expressions are given in table 16B. All tables in the text (except No. 24—see footnote in connection therewith) are now based on these more definitive values.

The symbols and terminology used throughout tables 16A, B are given below. The corresponding symbols of E. W. Brown's theory, employed in the *Improved Lunar Ephemeris*, as well as the notation used in the *Explanatory Supplement to the American Ephemeris and Nautical Almanac*, adopted throughout most of the present work, are also included:[5]

Table 16	*ILE*	*ESAE*
L = the "average" mean anomaly of the Moon (the angular distance, in longitude, of the Moon from its perigee)	$\ell = L - \omega$	$M = ☾ - \Gamma'$ (*not* the M of the first column)
L' = the mean anomaly of the Sun (the angular distance, in longitude, of the Sun from the solar perigee)	$\ell' = L' - \omega'$	$g = L - \Gamma$
F = the mean argument of latitude of the Moon (the angular distance, in longitude, of the Moon from its ascending node)	$F = L - ☊$	$F = ☾ - ☊$
D = the mean elongation of the Moon from the Sun (the angular distance, in longitude, between the Moon and Sun)	$D = L - L'$	$D = ☾ - L$
M = the mean longitude of the Moon $= F + ☊$	L	☾
S = the mean longitude of the Sun	L'	L
T = the period of time, in centuries, from 1900	T	T
Other Equivalents		
the mean longitude of the Moon's node	☊	☊
the mean longitude of the lunar perigee	ω	Γ'
the mean longitude of the solar perigee	ω'	Γ
the mean anomaly of the Moon	ℓ	M
the mean anomaly of the Sun	ℓ'	g

The values of the Julian Dates corresponding to syzygy given in column 1 of table 16 are printed out from programmed[6] magnetic tape compilations in the U.S. Naval Observatory, and are determined for the "mean instants" of syzygy. (See main Explanatory Comments for table 16.) The values may differ in tenths of a day from the values given in hours in column 2. These Julian Dates form a direct part of an evaluative procedure only in table 24, where an accuracy to a few tenths of a day is completely adequate.

Table 16A
Approximate Reduction Procedure

1. Column 2 gives the time of syzygy rounded off to the nearest hour. Syzygy is defined as the instant the celestial longitudes (or, alternatively, the right ascensions) of the Moon and Sun are the same, and hence the lunar elongation is equal to zero. Initially, the following approximate equation was used for the determination of the times of syzygy. The desired values were obtained by setting this expression representing the difference in longitude between that of the Moon and Sun equal to zero:

$$\lambda_{☾} - \lambda_{\odot} = D + 22{,}640 \sin L - 4{,}586 \sin (L - 2D) + 2{,}370 \sin 2D + 769 \sin 2L - 668 \sin L' \ldots$$

(All coefficients are in arc seconds.)

The results from this approximate formula were utilized finally only in table 24, where the least accuracy required is in tenths of a day. All other tables contain data derived from the refined formulae (table 16B).

2. The equation originally used for obtaining the geocentric equatorial horizontal parallax of the Moon at the instants of syzygy and perigee (cols. 4, 10) is given below. It represents a truncation of the more definitive expression included in table 16B after the 17th term in the series. Data based upon the more fully expanded series of table 16B have been recomputed for all tables included in the text.

$$
\begin{aligned}
\pi''_{☾} = 3{,}422.608 &+ 186.540 \cos L \\
&+ 34.312 \cos (L-2D) + 28.233 \cos 2D \\
&+ 10.166 \cos 2L + 3.086 \cos (L+2D) \\
&+ 1.918 \cos (L'-2D) + 1.444 \cos (L+L'-2D) \\
&+ 1.153 \cos (L-L') - 0.978 \cos D \\
&- 0.949 \cos (L+L') - 0.714 \cos (L-2F) \\
&+ 0.622 \cos 3L + 0.601 \cos (L-4D) \\
&- 0.400 \cos L' + 0.372 \cos (2L-4D) \\
&- 0.304 \cos (2L-2D) - 0.300 \cos (L'+2D) \ . \ . \ .
\end{aligned}
$$

(All coefficients are in arc seconds.)

3. Perigee (or proxigee) is that position in the orbit of the Moon where it reaches its closest approach to the Earth. At this point, the parallax (which varies inversely as the distance) attains its maximum value. Immediately prior to the position of perigee, the values of the parallax which have been increasing steadily (cf., figs. 37–38) begin to increase less rapidly, pass through a point of zero change at perigee, and then begin a steady decrease. At the instant of perigee, the *rate of change* in parallax denoted by $\pi_{☾}$ is, therefore, zero.

By differentiating the expression for $\pi_{☾}$ given in (2) and setting the resulting $\dot{\pi}_{☾}$ equal to zero at the maximum value of $\pi_{☾}$, the time of perigee is obtained. This approximate expression for $\pi_{☾}$ was used in the initial computation for the time of perigee (and hence that of the separation-interval P—S) in column 9 of table 16. The results calculated to this first degree of approximation have been incorporated only in table 24, where less stringent accuracies to the order of tenths of a day are involved. The corresponding series expansion given below represents a truncation of the more exact equation represented in table 16B following the sixth term.

$$
\begin{aligned}
\dot{\pi}_{☾} = -42.54 \sin L &+ 6.78 \sin (L-2D) \\
&- 12.01 \sin 2D - 4.64 \sin 2L \\
&- 2.02 \sin (L+2D) + 0.78 \sin (L'-2D) \ . \ . \ .
\end{aligned}
$$

(All coefficients are in arc seconds.)

Table 16B

Refined Reduction Formulae

1. The time of syzygy to the nearest hour (col. 2) is obtained by the use of the following improved equation for determining the difference in longitude between the Moon and Sun. The instant at which this expression, equated to 0°, shows that the lunar elongation is zero, corresponds to the time of syzygy.

$$
\begin{aligned}
\lambda_{☾} - \lambda_{\odot} = D + 18{,}222 \sin L &- 7{,}751 \sin L' \\
&- 471 \sin 2F + 470 \sin 2L \\
&- 321 \sin (L+L') + 190 \sin (L-L') \ . \ . \ .
\end{aligned}
$$

(All coefficients are in arc seconds.)

2. A more exact expression used to derive the geocentric equatorial horizontal parallax (cols. 4, 10) of the Moon at times of syzygy and perigee (applicable also at any position in its orbit) is:

$$
\begin{aligned}
\pi''_{☾} = 3{,}422.608 &+ 186.540 \cos L \\
&+ 34.312 \cos (L-2D) + 28.233 \cos 2D \\
&+ 10.166 \cos 2L + 3.086 \cos (L+2D) \\
&+ 1.918 \cos (L'-2D) + 1.444 \cos (L+L'-2D) \\
&+ 1.153 \cos (L-L') - 0.978 \cos D \\
&- 0.949 \cos (L+L') - 0.714 \cos (L-2F) \\
&+ 0.622 \cos 3L + 0.601 \cos (L-4D) \\
&- 0.400 \cos L' + 0.372 \cos (2L-4D) \\
&- 0.304 \cos (2L-2D) - 0.300 \cos (L'+2D) \\
&+ 0.283 \cos (2L+2D) + 0.261 \cos 4D \\
&+ 0.230 \cos (L-L'+2D) - 0.226 \cos (L-L'-2D) \\
&+ 0.149 \cos (L'+D) + 0.125 \cos (2L-L') \\
&- 0.119 \cos (3L-2D) - 0.109 \cos (L+D) \\
&- 0.105 \cos (2F-2D) - 0.103 \cos (2L+L') \\
&+ 0.092 \cos (2L'-2D) - 0.083 \cos (L+2F-2D) \\
&+ 0.067 \cos (L+L'-4D) + 0.048 \cos (L+2L'-2D) \\
&- 0.048 \cos (L+L'+2D) - 0.048 \cos (L-2F+2D) \\
&+ 0.044 \cos (L+4D) + 0.040 \cos 4L \\
&- 0.038 \cos (L-3D) + 0.035 \cos (L'-4D) \ . \ . \ .
\end{aligned}
$$

(All coefficients are in arc seconds.)

3. The reduction for the rate of orbital motion of the Moon with respect to the perigee is represented by the values given in degrees per day in cols. 5 and 11. These values result from the fact that the angular distance along the plane of the lunar orbit between the Moon and perigee is equal to the true anomaly $v_☾$. Accordingly, it is only necessary to differentiate the appropriate algorithmic expression for the true anomaly to obtain (in radians per day) the rate of motion of the Moon, in true anomaly. When the constant term $13.06499°/^d$ expressing the mean daily lunar velocity in the anomalistic month ($360°/27.554551^d$) is added to this derivative of the true anomaly $\dot{v}_☾$ (converted to $°/^d$), the result is equivalent to the Moon's daily angular velocity with respect to perigee.

The computer printout shows that even 169 terms are insufficient to reduce the numerical coefficient to zero in the fifth decimal place. The first 136 of these terms which were truncated after reaching a nearly integral digit 3 in the fifth decimal place and employed in the computation of cols. 5 and 11 are given below.

$$
\begin{aligned}
\dot{v}_☾ = +13.06499°/^d[&+0.05715 \cos (L-2D) \\
&+0.03578 \cos L - 0.01624\ (L+2D) \\
&-0.01350 \cos (2L-4D) + 0.00943 \cos 2D \\
&-0.00718 \cos (3L-4D) + 0.00558 \cos 2L \\
&-0.00510 \cos (2L-2D) + 0.00333 \cos 3L \\
&+0.00328 \cos (4L-6D) + 0.00313 \cos (L+L'-2D) \\
&+0.00290 \cos (3L-6D) - 0.00232 \cos (2L+2D) \\
&-0.00222 \cos (3L-2D) - 0.00154 \cos (2L+L'-4D) \\
&-0.00112 \cos (4L-2D) - 0.00102 \cos (5L-8D) \\
&+0.00093 \cos (4L-4D) - 0.00085 \cos (L-L'+2D) \\
&+0.00081 \cos (5L-6D) - 0.00080 \cos (3L+2D) \\
&+0.00077 \cos (2L+4D) - 0.00068 \cos (4L+2D) \\
&+0.00065 \cos (L'-2D) - 0.00064 \cos (L+4D) \\
&+0.00062 \cos 4L - 0.00060 \cos (4L-8D) \\
&-0.00060 \cos (3L+L'-4D) + 0.00059 \cos (6L-8D) \\
&-0.00054 \cos (5L-2D) + 0.00049 \cos (3L+L'-6D) \\
&+0.00048 \cos (4L+L'-6D) + 0.00048 \cos (5L-4D) \\
&+0.00048 \cos (L-L') - 0.00040 \cos (L-L'-2D) \\
&-0.00035 \cos (L-6D) - 0.00034 \cos (3L-L'+2D) \\
&+0.00029 \cos (6L-10D) - 0.00028 \cos (2L+L'-2D) \\
&+0.00024 \cos (6L-4D) + 0.00024 \cos (7L-10D) \\
&-0.00023 \cos (5L+L'-8D) - 0.00022 \cos (L'+2D) \\
&+0.00022 \cos (2L+L') + 0.00021 \cos (L'-4D) \\
&+0.00021 \cos (2L-L'-4D) + 0.00019 \cos (3L-2F-2D) \\
&+0.00019 \cos (2L-3D) - 0.00019 \cos L' \\
&+0.00018 \cos 4D + 0.00018 \cos (L-L'+4D) \\
&+0.00017 \cos (2L-L') - 0.00016 \cos (6L-6D) \\
&+0.00015 \cos (3L-L') - 0.00015 \cos (2L+L'+D) \\
&-0.00015 \cos (3L+L'-2D) - 0.00015 \cos (2L-L'+2D) \\
&-0.00015 \cos (4L+L'-8D) + 0.00015 \cos (3L+L') \\
&+0.00014 \cos (2L+2F+2D) + 0.00013 \cos (L+L') \\
&+0.00013 \cos (L+2L'-2D) + 0.00013 \cos (L+L'+2D) \\
&+0.00013 \cos (5L-10D) + 0.00012 \cos (L-2F) \\
&-0.00012 \cos (2L+L'+2D) - 0.00012 \cos (2L+2L'-4D) \\
&+0.00012 \cos (3L+4D) - 0.00011 \cos D \\
&+0.00011 \cos 5L - 0.00011 \cos (4L+L'-2D) \\
&+0.00011 \cos (2L'+2D) - 0.00010 \cos (6L-2D) \\
&+0.00010 \cos (3L+2F-2D) - 0.00010 \cos (6L+L'-8D) \\
&+0.00010 \cos (2L-8D) + 0.00010 \cos (5L+L'-6D) \\
&-0.00009 \cos (2L+D) + 0.00009 \cos (4L+L'-4D) \\
&-0.00009 \cos (7L-6D) - 0.00009 \cos (7L-8D) \\
&-0.00008 \cos (2L-2F-2D) - 0.00008 \cos (5L+2D) \\
&+0.00008 \cos (L-2F+2D) + 0.00008 \cos (8L-10D) \\
&+0.00008 \cos (7L-4D) - 0.00008 \cos (3L-5D) \\
&-0.00008 \cos (2L-2L') + 0.00008 \cos (2L+2F-2D) \\
&+0.00007 \cos (L-D) - 0.00007 \cos (4L-2F-4D) \\
&+0.00007 \cos 6L - 0.00007 \cos (8L-12D) \\
&-0.00007 \cos (3L-L'-6D) - 0.00007 \cos (L+6D) \\
&+0.00007 \cos (6L+L'-10D) - 0.00006 \cos (3L-L'-2D)
\end{aligned}
$$

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$$
\begin{aligned}
\text{(Continued)}&-0.00006 \cos (3L-2F+2D)+0.00006 \cos (2L-D)\\
&+0.00006 \cos (L+L'+4D)+0.00006 \cos (3L-L'-4D)\\
&+0.00006 \cos (L-L'-4D)+0.00006 \cos (4L-L')\\
&-0.00006 \cos (4L-L'+2D)+0.00005 \cos (4L+L')\\
&-0.00005 \cos (4L-5D)+0.00005 \cos (5L+L'-4D)\\
&+0.00005 \cos (L'+D)+0.00005 \cos (3L+2L'-6D)\\
&+0.00005 \cos (3L-8D)-0.00005 \cos (4L-L'-6D)\\
&+0.00005 \cos (7L+L'-10D)-0.00004 \cos (L'-6D)\\
&+0.00004 \cos (L'+4D)-0.00004 \cos (5L-2F-4D)\\
&-0.00004 \cos (2L+2F)+0.00004 \cos (2F+2D)\\
&+0.00004 \cos (5L-L')-0.00004 \cos (2F-4D)\\
&-0.00004 \cos (3L-3D)-0.00004 \cos (2L-L'-3D)\\
&-0.00004 \cos (9L-12D)-0.00004 \cos 6D\\
&+0.00004 \cos (L-4D)-0.00004 \cos (5L+L'-2D)\\
&+0.00004 \cos (L+3D)-0.00003 \cos (3L+2L'-4D)\\
&+0.00003 \cos (4L+2L'-6D)+0.00003 \cos (3L-D)\\
&+0.00003 \cos (L+2F-2D)-0.00003 \cos (4L-L'-2D)\\
&-0.00003 \cos (7L-12D)-0.00003 \cos (L-2L'+2D)\\
&-0.00003 \cos (2L-2L'+2D)+0.00003 \cos (2L-2F+2D)\\
&-0.00003 \cos (L+2F)\ .\ .\ .\ .]\ \text{radian/day.}
\end{aligned}
$$

(All coefficients are in radians.)

4. The following expression is used in computing the Moon's daily rate of angular motion in right ascension, $\alpha_{☾}$ (cols. 6, 12), determined for the instants of true syzygy and true perigee, respectively. This value represents lunar motion as it is projected into the plane of the celestial equator. As such, it more exactly represents the portion of the diurnal motion of the Earth (occurring in a plane either coincident with, or parallel to the Equator) through which it is necessary for any given meridian of the Earth to rotate in order to catch up on the Moon.

However, cyclically, over long periods, the calculated motions in right ascension show deviations from values consistent with the existing parallax. These deviations are the result of the effects of the 18.6-year nodical (draconitic) cycle which causes—in addition to a 5° increase in the range of the maximum declination of the Moon (fig. 36)—a much smaller but gravitationally effective variation in the extremes of lunar latitude. Such latitude excursions are responsible for periodic quantitative deviations in $\dot{\alpha}_{☾}$ from values to be expected from the existing parallax. These are approximately equal in magnitude to similar deviations caused by the solar parallactic inequality.

With these latter factors properly considered, a value obtained from this equation is useful in determining the additional angular motion necessary for a given terrestrial meridian to catch up with the Moon and occasion a lunar transit, subject to the Earth's rotation in, or parallel to, the same equatorial plane.

$$
\begin{aligned}
\dot{\alpha}_{☾}=13.17640°[&+5{,}162 \cos L-4{,}067 \cos 2M\\
&-1{,}756 \cos (F+M)+1{,}008 \cos 2D\\
&+906 \cos (L-2D)-668 \cos (L+2M)\\
&+351 \cos 2L-288 \cos (L+M+F)\\
&+227 \cos (L-2M)-191 \cos 2F\\
&+176 \cos 4M+149 \cos (3M+F)\\
&+127 \cos (L+2D)-121 \cos (L-2M-2D)\\
&-107 \cos (2M+2D)+97 \cos (L-M-F)\\
&-80 \cos (2L+2M)-75 \cos (3M-F)\\
&+68 \cos (L'-2D)+53 \cos (L+2M-2D)\\
&-53 \cos (L-M-F-2D)+51 \cos (2M+2F)\\
&+48 \cos (L+4M)-46 \cos (M+2D-F)\\
&-44 \cos (M+F+2D)+41 \cos (L+3M+F)\\
&+37 \cos (L+L'-2D)-34 \cos (2L+M+F)\\
&-33 \cos (L+2F)+31 \cos (L-L')\\
&-29 \cos (L-4M)-27 \cos (L+L')\\
&-27 \cos D+26 \cos 3L\\
&-25 \cos (L-3M-F)-24 \cos (L+2M+2D)\\
&+23 \cos (L-4D)+23 \cos (L+M+F-2D)\\
&+15 \cos (2L+2M-2D)+14 \cos (2L+2D)\\
&+14 \cos (2L-4D)+14 \cos (L'+2M)\\
&-13 \cos (L'-2M)-13 \cos (L+3M-F)\\
&-12 \cos L'-11 \cos (L'+2D)
\end{aligned}
$$

$$
\begin{aligned}
&(\text{Continued}) + 10 \cos 4D + 10 \cos (L - L' + 2D) \\
&\quad - 10 \cos (L - 2F) - 10 \cos (L + M - F + 2D) \\
&\quad + 8 \cos (L + 2M + 2F) - 7 \cos (5M + F) \\
&\quad + 7 \cos (M + 3F)]/3{,}600''.
\end{aligned}
$$

(All coefficients are in arc seconds.)

---

5. The expression used in obtaining the apparent declination of the Moon at the time of true syzygy (col. 7) and true perigee (col. 13), which is also applicable at any time in the lunar orbit, is:

$$
\begin{aligned}
\delta^{\circ}_{\text{☾}} = [&83{,}523 \sin M +]17{,}662 \sin F \\
&+ 4{,}599 \sin (L - M) + 4{,}570 \sin (L + M) \\
&+ 964 \sin (L + F) + 954 \sin (L - F) \\
&- 952 \sin (L + M - 2D) - 903 \sin (L - M - 2D) \\
&- 594 \sin (F - 2D) - 578 \sin 3M \\
&+ 517 \sin (M + 2D) - 434 \sin (M - 2D) \\
&+ 374 \sin (2M - F) - 366 \sin (2M + F) \\
&+ 274 \sin (2L + M) - 183 \sin (L - F - 2D) \\
&- 153 \sin (L + F - 2D) - 133 \sin (L' + M) \\
&- 133 \sin (L' - M) + 108 \sin (F + 2D) \\
&- 101 \sin (2F - M) - 93 \sin (2L + M - 2D) \\
&- 88 \sin (L - 3M) - 87 \sin (L + 3M) \\
&+ 67 \sin (L + M + 2D) - 65 \sin (M + 2F) \\
&+ 57 \sin (2L + F) - 54 \sin (L - F - 2M) \\
&- 54 \sin (L + F + 2M) - 47\, T \sin M \\
&- 41 \sin (L + L' + M - 2D) - 41 \sin (L + L' - M - 2D) \\
&- 33 \sin (L' + M - 2D) - 33 \sin (L' - M - 2D) \\
&+ 31 \sin (L - F + 2D) + 30 \sin (2L - M) \\
&+ 29 \sin (L - L' + M) + 29 \sin (L - L' - M) \\
&+ 29 \sin (2L - F) - 27 \sin (L' + F - 2D) \\
&- 25 \sin (M + D) + 25 \sin (M - D) \\
&- 22 \sin (L + L' + M) - 22 \sin (L + L' - M) \\
&+ 19 \sin (L + 3M - 2D) + 18 \sin (L - 2M + F) \\
&+ 18 \sin (L + 2M - F) + 17 \sin (L - 3M - 2D) \\
&+ 14 \sin (2M + F - 2D) - 14 \sin (2L + F - 2D) \\
&+ 14 \sin (L + F + 2D) + 13 \sin (L - M - 2F) \\
&+ 13 \sin (L + M + 2F)]/3{,}600''.
\end{aligned}
$$

(All coefficients are in arc seconds.)

---

6. The corresponding declination of the Sun at the instant of true syzygy (col. 8) and true perigee (col. 14)—or any other time in the apparent annual motion of the Sun—is given by:

$$
\begin{aligned}
\delta^{\circ}_{\odot} = [&83{,}797 \sin S + 1{,}404 \sin (L' - S) \\
&+ 1{,}403 \sin (L' + S) - 594 \sin 3S \\
&- 46\, T \sin S - 30 \sin (L' - 3S) \\
&- 30 \sin (L' + 3S) \\
&+ 26 \sin (2L' + S)]/3{,}600''.
\end{aligned}
$$

(All coefficients are in arc seconds.)

---

7. The expression used to obtain the time of perigee and hence the separation-interval $P - S$ (col. 9) by differentiating expression (2) and setting $\dot{\pi}_{\text{☾}}$ (the rate of change in parallax) equal to zero at the maximum value of $\pi_{\text{☾}}$ is given below. Because of the mathematical assumptions used, this expression is the most accurate near the alignment of perigee and syzygy.

$$
\begin{aligned}
\dot{\pi}_{\text{☾}} = &-42.54 \sin L + 6.78 \sin (L - 2D) \\
&- 12.01 \sin 2D - 4.64 \sin 2L \\
&- 2.02 \sin (L + 2D) + 0.78 \sin (L' - 2D) \\
&+ 0.26 \sin (L + L' - 2D) - 0.24 \sin (L - L') \\
&+ 0.23 \sin (L + L') - 0.17 \sin (L - 2F) \\
&+ 0.37 \sin (L - 4D) - 0.43 \sin (L + 2L) \\
&- 0.25 \sin (2L + 2D) - 0.22 \sin 4D
\end{aligned}
$$

$$(\text{Continued}) + 0.21 \sin D - 0.15 \sin (L - L' + 2D) + 0.15 \sin (2L - 4D) + 0.13 \sin (L' + 2D) - 0.06 \sin (2L - L') \ldots$$

(All coefficients are in arc seconds.)

In considering the computer printout of table 16, two important characteristics common to such close perigee-syzygy alignments are readily discernible:

1. This table is based upon a maximum separation-interval of $\pm 24^h$ between perigee and syzygy. Accepting this arbitrary 24-hour interval between the two astronomical configurations as defining the upper limit of a typical close alignment of perigee-syzygy, it is obvious that such close alignments almost invariably occur in pairs, averaging 29.5 days apart. These occurrences are followed and preceded, in the average case, by another such pair, one component of which is separated by approximately 6.5 or 7.5 periods of 29.5 days from its matching component in the first pair having the smallest interval between perigee and syzygy. (Sometimes, however, as the result of the limiting 24-hour perigee-syzygy separation-interval, one component of either pair may be eliminated.) Either of the components in each pair may have the smaller separation-interval between perigee and syzygy. This results in the corresponding variable length of time (i.e., 6.5 or 7.5 periods of 29.5 days) between it and the component having the smallest separation-interval in the preceding or following pair.

2. Since lunar months rather than calendar months are involved in the succession of perigee-syzygy events, one or both components of any pair may also overlap 2 consecutive calendar years. The tropical or calendar year, usually (but not always) containing four ordinary perigee-syzygy alignments with a separation-interval $\leq 24^h$, consists of 12.37 synodic months. Thus, the successive pairs belonging to a perigee-syzygy cycle of 6.5 or 7.5 periods of 29.5 days can easily lie in different calendar years, and due care must be exercised in relating these cycles over long periods of time.

Table 16

Designation of Columns

Table 16 is reproduced by electronic composition directly from a computer printout of lunar and solar data provided by the Nautical Almanac Office, U.S. Naval Observatory. This table contains data pertinent to all cases between the years 1600 and 1999 in which lunar perigee and syzygy occur within ± 24 mean solar hours of each other.

The arrangement of this table is as follows:

Col. 1 gives the Julian Date to the nearest 0.1 day, corresponding to the time of mean syzygy. This position is based upon the mean apparent motions of the Moon ($13.176396°/^d$) and Sun ($0.985647°/^d$) and represents the average time at which these two bodies reach syzygy alignment. The apparent discrepancy between the decimal portion of the Julian Day and the time (in hours) given for syzygy in column 2 is due to the fact that the latter time corresponds to true rather than mean syzygy. For any date in history, the Julian Day also starts at noon (Greenwich mean time), whereas all of the times given in column 2 are in Greenwich civil time (or more exactly, ephemeris time) which begins at midnight.

The inclusion of these Julian Dates makes more convenient the subtraction of differences in time, and the establishment of related periodicities between individual occurrences of perigee-syzygy. It is also possible by means of this artifice to determine the day of the week for any instance of tidal flooding, making possible the cross checking of early documentary sources of such flooding.

For all practical purposes, one-half of the difference in hours (col. 9) between true perigee and true syzygy may be algebraically added (as a decimal part of a day) to the Julian Date of mean syzygy to obtain the approximate mean date of perigee-syzygy. Proper allowance must also be made to convert from ephemeris time at Greenwich to local standard time at the location of the flooding by subtraction of the appropriate number of hours which the station is west of Greenwich. For example, in establishing the corresponding day of the week in eastern standard time, 5 hours (0.2^d) is subtracted from the Julian Date. The date and decimal portion are then rounded off to the nearest unit. Any resulting decimal value of 0.5^d is rounded off, in practice, to the nearest *even* unit, either higher or lower, as the case may be.

The appropriate day of the week is obtained by dividing the entire rounded-off Julian Date by 7. If the remainder is 0, the day is Monday, if 1, Tuesday, etc., through a remainder of 6 for Sunday.

Column 2 contains the year, month, date, and 24-hour time of *true* syzygy (rounded off to the nearest hour) for each case of syzygy associated with a perigee-syzygy alignment in which the two components occur within the prescribed separation-interval of ± 24 hours or less.

All dates, regardless of year, are given in the Gregorian (New Style) Calendar. Prior to 1752, if Old Style dates are desired for comparison purposes, the tabulated dates must be corrected according to the procedure outlined at the close of part I, chapter 1.

In the data processing procedure, the necessary reductions have been made, and all times given are in ephemeris time, which corresponds very closely with Greenwich civil time.

Using data referred consistently to Greenwich *civil* time throughout this and subsequent columns of the table, no adjustment is needed for the fact that, after January 1, 1925, the beginning of the astronomical day changed from noon (Greenwich mean time) to the preceding midnight (Greenwich civil time). To convert to eastern standard time, 5 hours should be subtracted; Pacific standard time similarly is 8 hours earlier.

Because of rounding-off and data-truncating procedures used in the computer processing, the times given in this column will not, in all cases, agree exactly with those contained in *The American Ephemeris and Nautical Almanac* and other ephemerides, or as reproduced in various governmental tide tables. Where rounding-off errors combine in the same direction, the differences may amount to as much as an hour. The more accurate ephemeris values have been used in all cases throughout the text where times to the accuracy of minutes are involved; however, the present tabular values will suffice for all instances in which values accurate to the nearest hour are required.

Column 3 indicates the phase of syzygy as either new moon (N) or full moon (F).

Column 4 lists the geocentric horizontal parallax in minutes, seconds, and tenths of seconds of arc, corresponding to the time of true syzygy.

Column 5 contains a series of angular values expressing the rate of orbital motion of the Moon with respect to the perturbed motion of perigee, determined, for the instant of syzygy, in $°/^d$. The procedure by which this value is calculated from the time rate of change of the Moon's true anomaly is explained in the Introduction to table 16.

The method of using this angle, and that from column 6, to obtain the special value designated in this monograph as the "$\Delta\omega$-syzygy coefficient" is described in chapter 8. This coefficient represents the astronomical portion of a total quantifier indicating the potential for tidal flooding associated with the simultaneous occurrence of perigean spring tides and strong, persistent, onshore winds.

Column 6 tabulates the orbital motion of the Moon in right ascension (expressed likewise, for comparative purposes, in $^\circ/^d$) at the instant of true syzygy.

Column 7 is a tabulation of the apparent declination of the Moon (to the nearest degree) at the time of true syzygy.

Column 8 notes the apparent declination of the Sun (to the nearest degree) at the time of true syzygy.

Column 9 indicates the increment or decrement (in hours) which, according to algebraic sign, it is necessary to add to, or subtract from, the time of true syzygy in column 2 in order to find the corresponding time of true perigee. This difference in time is consistently taken in the sense perigee minus syzygy, and represents the perigee-syzygy "separation-interval" frequently referred to throughout the volume. With the exception of a few cases caused by the combination of rounding-off errors, no value in column 9 exceeds ± 24 hours.

The *mean epoch of perigee syzygy* (see column 8 of table 1) is obtained by dividing the figure in column 9 by 2 and adding the result algebraically to the time of syzygy in column 2.

Column 10 designates the geocentric horizontal parallax of the Moon (in minutes and seconds of arc), in the same manner as column 4, but now as it applies to the slightly different time and position of true perigee.

Column 11 repeats the instantaneous value of the rate of the Moon's motion with respect to perigee (in $^\circ/^d$) described under column 5, but now referred to the time of true perigee.

Column 12 gives the orbital motion of the Moon in right ascension (expressed also in $^\circ/^d$) for the instant of true perigee.

Column 13 reproduces column 7, but gives the apparent declination of the Moon (in degrees) at the time of true perigee.

Column 14 provides the corresponding apparent declination of the Sun (in degrees) at the time of true perigee.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2305521.3	1600/ 3/15– 4	N	61 10.3	16.984	13.616	1.8	– 2.1	17	61 15.8	16.974	13.830	6.7	– 1.8
2305550.9	1600/ 4/13–12	N	61 25.1	16.974	14.580	13.9	9.2	– 4	61 25.3	16.971	14.465	12.9	9.1
2305742.8	1600/10/22– 5	F	61 25.6	17.019	14.920	15.7	–11.1	10	61 27.0	17.017	15.236	17.6	–11.3
2305772.3	1600/11/20–15	F	61 21.7	17.091	16.404	23.3	–19.9	–12	61 24.5	17.073	16.076	21.8	–19.8
2305934.8	1601/ 5/ 2–13	N	61 9.0	16.895	15.511	19.2	15.4	17	61 14.0	16.916	16.058	21.7	15.6
2305964.3	1601/ 5/31–20	N	61 21.5	16.962	16.670	24.0	22.0	– 4	61 21.9	16.958	16.621	23.7	21.9
2306156.2	1601/12/ 9–18	F	61 27.1	17.140	16.677	23.4	–22.9	7	61 28.0	17.139	16.667	23.3	–22.9
2306185.8	1602/ 1/ 8– 5	F	61 17.9	17.090	15.851	20.1	–22.2	–15	61 21.8	17.086	16.248	21.8	–22.3
2306348.2	1602/ 6/19–20	N	61 7.9	16.892	16.316	22.2	23.4	18	61 12.9	16.889	16.086	21.0	23.4
2306377.7	1602/ 7/19– 3	N	61 21.8	16.937	15.515	17.5	21.0	– 4	61 22.1	16.941	15.630	18.2	21.0
2306569.7	1603/ 1/27– 7	F	61 29.9	17.103	15.152	14.1	–18.5	5	61 30.2	17.099	15.051	13.3	–18.5
2306599.2	1603/ 2/25–17	F	61 15.0	16.979	14.245	4.4	– 9.0	–17	61 20.1	16.960	14.498	8.3	– 9.3
2306761.6	1603/ 8/ 7– 3	N	61 10.5	16.872	14.817	11.9	16.6	17	61 15.3	16.850	14.540	8.6	16.4
2306791.2	1603/ 9/ 5–11	N	61 24.0	16.974	14.342	2.7	7.0	– 5	61 24.4	16.975	14.371	3.6	7.0
2306983.1	1604/ 3/15–19	F	61 28.0	17.047	14.434	– 1.4	– 1.8	2	61 28.1	17.049	14.444	– 1.9	– 1.8
2307012.6	1604/ 4/14– 4	F	61 9.0	16.926	14.790	–10.6	9.4	–20	61 15.1	16.905	14.548	– 6.9	9.2
2307175.0	1604/ 9/23–12	N	61 12.0	16.971	14.389	– 2.5	– 0.3	16	61 16.4	16.962	14.542	– 5.8	– 0.5
2307204.6	1604/10/22–21	N	61 24.1	17.089	15.031	–11.3	–11.4	– 5	61 24.7	17.091	14.941	–10.4	–11.3
2307367.0	1605/ 4/ 3–20	F	60 58.8	16.917	14.457	– 5.9	5.5	24	61 8.3	16.920	14.838	–10.3	5.9
2307396.5	1605/ 5/ 3– 5	F	61 25.5	16.982	15.351	–13.6	15.6	1	61 25.6	16.982	15.382	–13.9	15.7
2307426.1	1605/ 6/ 1–12	F	61 6.8	16.820	15.861	–18.0	22.1	–20	61 13.3	16.816	15.663	–16.5	22.0
2307588.5	1605/11/10–23	N	61 17.7	17.058	15.386	–14.3	–17.4	15	61 21.1	17.034	15.656	–15.9	–17.6
2307618.0	1605/12/10–10	N	61 26.0	17.084	16.074	–18.2	–22.9	– 8	61 27.1	17.083	16.023	–17.9	–22.9
2307780.4	1606/ 5/22– 5	F	61 0.5	16.803	15.486	–15.9	20.3	23	61 9.5	16.796	15.853	–17.7	20.5
2307810.0	1606/ 6/20–12	F	61 26.0	16.893	16.109	–18.4	23.4	1	61 26.1	16.894	16.111	–18.4	23.4
2307839.5	1606/ 7/19–19	F	61 7.2	16.827	15.651	–16.6	20.8	–20	61 13.7	16.815	15.923	–17.9	21.0
2308001.9	1606/12/29–12	N	61 21.8	17.073	16.091	–18.5	–23.2	12	61 24.2	17.068	16.052	–18.2	–23.2
2308031.4	1607/ 1/27–22	N	61 23.0	17.096	15.584	–15.4	–18.3	–10	61 24.7	17.083	15.766	–16.5	–18.5
2308193.9	1607/ 7/ 9–12	F	60 59.4	16.777	15.879	–18.6	22.4	23	61 8.4	16.778	15.683	–17.1	22.3
2308223.4	1607/ 8/ 7–19	F	61 24.9	16.962	15.478	–14.8	16.5	2	61 25.0	16.962	15.446	–14.6	16.4
2308252.9	1607/ 9/ 6– 3	F	61 5.9	16.920	14.574	– 7.5	6.7	–20	61 12.7	16.929	14.923	–11.0	7.0
2308415.3	1608/ 2/16– 1	N	61 21.7	17.101	15.144	–12.8	–12.6	9	61 23.3	17.100	14.979	–11.2	–12.5
2308444.9	1608/ 3/16–11	N	61 18.2	17.016	14.443	– 4.1	– 1.5	–13	61 20.8	17.012	14.581	– 6.6	– 1.7
2308607.3	1608/ 8/25–19	F	61 1.3	16.861	14.825	–12.0	10.5	24	61 10.0	16.830	14.500	– 7.6	10.2
2308636.8	1608/ 9/24– 4	F	61 27.9	17.016	14.413	– 2.9	– 0.5	1	61 27.9	17.015	14.407	– 2.7	– 0.5
2308666.3	1608/10/23–13	F	61 7.1	16.965	14.401	7.0	–11.6	–21	61 14.4	16.953	14.270	2.6	–11.3
2308828.8	1609/ 4/ 4–12	N	61 22.5	16.988	14.252	1.4	5.8	8	61 23.6	16.989	14.297	3.2	5.9
2308858.3	1609/ 5/ 3–20	N	61 16.2	16.917	14.727	11.2	15.8	–13	61 19.2	16.898	14.503	8.4	15.7
2309020.7	1609/10/13– 5	F	61 6.9	16.915	14.080	3.2	– 7.8	22	61 14.5	16.887	14.378	8.1	– 8.1
2309050.2	1609/11/11–15	F	61 30.4	17.088	14.987	13.3	–17.6	– 1	61 30.4	17.088	14.977	13.2	–17.6
2309079.8	1609/12/11– 1	F	61 3.5	17.039	15.934	20.5	–23.0	–23	61 12.3	16.998	15.456	17.6	–22.9
2309242.2	1610/ 5/22–20	N	61 19.8	16.941	15.393	17.3	20.4	8	61 20.8	16.951	15.616	18.6	20.5
2309271.7	1610/ 6/21– 3	N	61 12.9	16.920	16.379	22.6	23.4	–13	61 16.1	16.914	16.157	21.5	23.4
2309434.1	1610/11/30–17	F	61 10.5	17.046	15.659	19.8	–21.7	19	61 16.8	17.037	16.229	22.3	–21.8
2309463.7	1610/12/30– 4	F	61 29.4	17.156	16.764	24.0	–23.2	– 3	61 29.6	17.156	16.750	23.9	–23.2

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2309655.6	1611/ 7/10– 4	N	61 19.5	16.943	16.759	24.7	22.3	7	61 20.5	16.937	16.681	24.3	22.3
2309685.1	1611/ 8/ 8–11	N	61 14.1	16.897	15.686	20.3	16.3	–14	61 17.2	16.912	16.131	22.3	16.4
2309847.6	1612/ 1/18– 6	F	61 16.1	17.076	16.529	24.3	–20.6	17	61 20.9	17.048	16.105	22.4	–20.5
2309877.1	1612/ 2/16–17	F	61 29.2	17.060	15.080	17.0	–12.4	– 6	61 29.7	17.059	15.271	18.1	–12.4
2310069.0	1612/ 8/26–11	N	61 22.3	16.944	14.634	14.9	10.3	7	61 23.3	16.937	14.406	13.1	10.2
2310098.6	1612/ 9/24–19	N	61 15.5	16.984	13.616	2.9	– 0.8	–14	61 18.9	16.981	13.801	6.8	– 0.6
2310261.0	1613/ 3/ 6–18	F	61 17.4	17.009	13.896	9.4	– 5.4	15	61 21.2	17.009	13.673	5.3	– 5.2
2310290.5	1613/ 4/ 5– 3	F	61 24.9	17.013	13.630	– 3.8	6.1	– 7	61 25.7	17.006	13.586	– 1.8	5.9
2310482.5	1613/10/13–21	N	61 23.7	17.063	13.694	– 6.9	– 8.0	6	61 24.4	17.061	13.821	– 8.7	– 8.1
2310512.0	1613/11/12– 7	N	61 13.9	17.070	15.053	–19.2	–17.8	–16	61 18.1	17.068	14.484	–15.4	–17.6
2310674.4	1614/ 4/24– 4	F	61 16.0	16.965	14.182	–13.5	12.8	14	61 19.3	16.966	14.699	–17.1	12.9
2310704.0	1614/ 5/23–12	F	61 22.6	16.926	16.049	–23.7	20.6	– 7	61 23.5	16.926	15.734	–22.3	20.5
2310895.9	1614/12/ 1– 9	N	61 28.0	17.098	16.653	–25.9	–21.8	4	61 28.4	17.094	16.805	–26.4	–21.9
2310925.4	1614/12/30–19	N	61 12.9	17.037	17.165	–28.1	–23.1	–17	61 18.3	17.013	17.268	–28.2	–23.2
2311087.9	1615/ 6/11–12	F	61 17.0	16.859	17.129	–27.9	23.1	14	61 20.1	16.852	17.309	–28.4	23.1
2311117.4	1615/ 7/10–19	F	61 23.2	16.888	16.906	–27.0	22.2	– 8	61 24.2	16.885	17.110	–27.6	22.3
2311279.8	1615/12/20–11	N	60 59.6	16.987	17.129	–28.3	–23.4	24	61 9.3	16.943	16.909	–27.3	–23.4
2311309.3	1616/ 1/18–22	N	61 28.6	17.105	16.241	–24.4	–20.5	1	61 28.7	17.106	16.167	–24.1	–20.5
2311338.9	1616/ 2/17– 8	N	61 6.6	17.020	14.096	–13.8	–12.1	–21	61 13.5	16.985	14.925	–19.0	–12.4
2311501.3	1616/ 7/28–19	F	61 16.0	16.891	15.509	–21.7	18.8	14	61 19.1	16.890	14.944	–18.6	18.7
2311530.8	1616/ 8/27– 2	F	61 22.4	16.986	13.894	–10.5	10.0	– 7	61 23.4	16.987	14.116	–12.6	10.1
2311693.2	1617/ 2/ 6– 0	N	61 2.2	17.030	14.527	–16.7	–15.6	22	61 10.4	17.017	13.870	–10.9	–15.3
2311722.8	1617/ 3/ 7–10	N	61 26.0	17.082	13.551	– 3.7	– 5.1	0	61 26.0	17.082	13.555	– 3.8	– 5.1
2311752.3	1617/ 4/ 5–19	N	61 1.1	16.895	13.731	9.8	6.3	–22	61 9.4	16.876	13.432	3.3	6.0
2311914.7	1617/ 9/15– 4	F	61 19.0	16.974	13.499	– 0.6	3.0	13	61 21.8	16.957	13.558	3.3	2.8
2311944.2	1617/10/14–12	F	61 24.9	17.027	14.215	12.4	– 8.3	– 8	61 26.3	17.029	14.002	10.2	– 8.2
2312106.7	1618/ 3/26–12	N	61 5.3	16.944	13.634	6.1	2.3	20	61 12.3	16.936	14.106	11.6	2.6
2312136.2	1618/ 4/24–20	N	61 25.2	16.962	15.053	17.7	13.0	– 1	61 25.2	16.961	14.998	17.4	13.0
2312165.7	1618/ 5/24– 3	N	60 59.0	16.820	16.436	25.0	20.7	–23	61 7.9	16.786	15.740	21.9	20.5
2312328.1	1618/11/ 2–14	F	61 23.7	17.025	15.434	19.4	–14.8	11	61 25.9	17.021	15.868	21.5	–15.0
2312357.7	1618/12/ 2– 0	F	61 24.6	17.109	16.859	25.4	–21.9	–10	61 26.6	17.095	16.674	24.7	–21.9
2312520.1	1619/ 5/13–20	N	61 4.0	16.855	15.993	22.3	18.4	20	61 10.6	16.880	16.547	24.4	18.6
2312549.6	1619/ 6/12– 4	N	61 22.1	16.958	16.866	25.2	23.1	– 2	61 22.1	16.956	16.868	25.2	23.1
2312579.1	1619/ 7/11–11	N	60 56.3	16.825	15.795	21.7	22.2	–24	61 5.3	16.837	16.482	24.3	22.3
2312741.6	1619/12/21– 3	F	61 25.4	17.138	16.674	24.0	–23.4	9	61 26.9	17.136	16.536	23.4	–23.4
2312771.1	1620/ 1/19–14	F	61 20.9	17.095	15.404	18.2	–20.4	–13	61 23.8	17.094	15.832	20.4	–20.5
2312933.5	1620/ 6/30– 4	N	61 3.3	16.865	16.113	22.0	23.2	20	61 10.0	16.859	15.651	19.5	23.1
2312963.0	1620/ 7/29–11	N	61 22.8	16.950	15.067	15.4	18.7	– 2	61 22.9	16.952	15.111	15.7	18.7
2312992.6	1620/ 8/27–18	N	60 58.0	16.834	13.961	5.3	9.8	–23	61 7.0	16.856	14.424	10.9	10.1
2313155.0	1621/ 2/ 6–16	F	61 28.2	17.090	14.680	11.1	–15.4	6	61 29.0	17.083	14.553	9.6	–15.3
2313184.5	1621/ 3/ 8– 2	F	61 18.3	16.978	14.090	0.3	– 4.9	–16	61 22.1	16.963	14.184	3.9	– 5.1
2313346.9	1621/ 8/17–11	N	61 6.3	16.863	14.394	8.7	13.4	20	61 12.8	16.834	14.186	4.3	13.1
2313376.5	1621/ 9/15–19	N	61 25.4	16.992	14.243	– 1.5	2.8	– 2	61 25.5	16.992	14.239	– 1.1	2.8
2313406.0	1621/10/15– 4	N	60 57.5	16.951	14.619	–11.5	– 8.5	–25	61 7.3	16.931	14.290	– 6.4	– 8.2
2313568.4	1622/ 3/27– 3	F	61 26.4	17.024	14.485	– 5.7	2.5	5	61 26.8	17.027	14.547	– 6.8	2.6

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2313598.0	1622/ 4/25–11	F	61 12.8	16.932	15.184	–14.4	13.2	–16	61 17.4	16.914	14.873	–11.5	13.0
2313760.4	1622/10/ 4–20	N	61 8.5	16.969	14.475	– 6.8	– 4.5	19	61 14.3	16.956	14.797	–10.4	– 4.8
2313789.9	1622/11/ 3– 6	N	61 25.8	17.107	15.437	–15.0	–15.1	– 4	61 26.0	17.108	15.370	–14.5	–15.0
2313981.9	1623/ 5/14–12	F	61 24.3	16.965	15.728	–16.6	18.6	5	61 24.6	16.965	15.802	–17.0	18.6
2314011.4	1623/ 6/12–19	F	61 11.3	16.839	16.055	–19.1	23.1	–17	61 16.1	16.838	16.013	–18.7	23.1
2314173.8	1623/11/22– 8	N	61 14.7	17.058	15.738	–16.9	–20.1	16	61 19.2	17.029	15.978	–18.1	–20.3
2314203.3	1623/12/21–19	N	61 27.7	17.091	16.150	–18.7	–23.4	– 6	61 28.3	17.091	16.166	–18.7	–23.4
2314395.3	1624/ 6/30–19	F	61 25.2	16.889	16.044	–18.1	23.1	5	61 25.5	16.888	16.011	–17.9	23.1
2314424.8	1624/ 7/30– 2	F	61 12.1	16.860	15.347	–14.3	18.5	–17	61 16.9	16.852	15.663	–16.2	18.7
2314587.2	1625/ 1/ 8–21	N	61 18.8	17.063	15.891	–17.5	–22.1	14	61 22.1	17.055	15.737	–16.4	–22.0
2314616.8	1625/ 2/ 7– 7	N	61 24.6	17.092	15.204	–12.3	–15.2	– 8	61 25.8	17.082	15.356	–13.5	–15.3
2314808.7	1625/ 8/18– 2	F	61 24.5	16.970	15.098	–11.5	13.1	5	61 24.8	16.969	15.028	–10.7	13.1
2314838.2	1625/ 9/16–11	F	61 10.9	16.965	14.454	– 3.2	2.5	–18	61 16.1	16.970	14.635	– 6.6	2.8
2315000.7	1626/ 2/26– 9	N	61 18.7	17.078	14.783	– 8.9	– 8.6	12	61 21.1	17.078	14.650	– 6.7	– 8.5
2315030.2	1626/ 3/27–19	N	61 20.3	17.013	14.442	0.3	2.8	–10	61 22.0	17.009	14.470	– 1.8	2.6
2315222.1	1626/10/ 5–12	F	61 28.0	17.033	14.451	1.4	– 4.8	3	61 28.2	17.030	14.463	2.1	– 4.9
2315251.7	1626/11/ 3–21	F	61 12.1	17.002	14.794	10.6	–15.3	–18	61 17.9	16.989	14.559	7.1	–15.0
2315414.1	1627/ 4/15–20	N	61 19.6	16.961	14.433	5.4	9.8	10	61 21.5	16.963	14.574	7.6	10.0
2315443.6	1627/ 5/15– 4	N	61 18.8	16.917	15.167	14.0	18.7	–11	61 20.8	16.903	14.953	12.1	18.6
2315606.0	1627/10/24–13	F	61 2.3	16.910	14.312	7.1	–11.8	24	61 11.5	16.877	14.795	11.9	–12.1
2315635.6	1627/11/22–23	F	61 30.6	17.098	15.453	15.9	–20.3	2	61 30.7	17.099	15.492	16.2	–20.3
2315665.1	1627/12/22–10	F	61 8.3	17.061	16.175	20.9	–23.4	–21	61 15.6	17.026	15.920	19.4	–23.4
2315827.5	1628/ 6/ 2– 4	N	61 17.1	16.919	15.781	19.0	22.2	10	61 19.0	16.930	16.027	20.2	22.3
2315857.0	1628/ 7/ 1–11	N	61 16.0	16.935	16.428	22.2	23.1	–11	61 18.1	16.933	16.378	21.9	23.1
2316019.5	1628/12/11– 2	F	61 6.2	17.037	16.011	21.1	–23.0	21	61 14.0	17.023	16.428	22.7	–23.1
2316049.0	1629/ 1/ 9–13	F	61 29.8	17.155	16.604	22.8	–22.0	– 1	61 29.8	17.155	16.612	22.8	–22.0
2316078.5	1629/ 2/ 7–23	F	61 2.3	16.971	15.375	18.1	–15.0	–23	61 11.3	16.957	16.054	21.2	–15.3
2316240.9	1629/ 7/20–11	N	61 17.3	16.939	16.416	22.9	20.6	11	61 19.2	16.928	16.211	21.9	20.5
2316270.5	1629/ 8/18–18	N	61 17.6	16.927	15.207	16.9	12.9	–11	61 19.7	16.940	15.555	18.8	13.1
2316432.9	1630/ 1/28–15	F	61 11.9	17.054	15.980	21.7	–18.1	19	61 18.0	17.021	15.437	18.8	–17.8
2316462.4	1630/ 2/27– 1	F	61 29.7	17.049	14.628	12.9	– 8.4	– 3	61 29.9	17.049	14.720	13.7	– 8.4
2316654.4	1630/ 9/ 6–19	N	61 20.7	16.949	14.249	10.9	6.3	10	61 22.4	16.939	14.043	8.3	6.1
2316683.9	1630/10/ 6– 3	N	61 19.2	17.015	13.706	– 1.3	– 5.1	–11	61 21.5	17.011	13.730	1.8	– 4.9
2316846.3	1631/ 3/18– 3	F	61 13.0	16.972	13.687	5.1	– 1.1	17	61 18.1	16.974	13.622	0.3	– 0.8
2316875.8	1631/ 4/16–11	F	61 25.8	17.001	13.915	– 7.8	10.1	– 4	61 26.1	16.996	13.839	– 6.5	10.0
2317067.8	1631/10/25– 5	N	61 22.5	17.071	14.055	–10.8	–12.0	9	61 23.8	17.067	14.307	–13.1	–12.1
2317097.3	1631/11/23–15	N	61 17.6	17.093	15.694	–21.8	–20.4	–13	61 20.7	17.091	15.183	–19.1	–20.3
2317259.7	1632/ 5/ 4–12	F	61 11.7	16.927	14.668	–16.9	16.1	17	61 16.4	16.929	15.363	–20.6	16.3
2317289.3	1632/ 6/ 2–20	F	61 24.0	16.926	16.559	–25.4	22.3	– 5	61 24.4	16.927	16.387	–24.7	22.3
2317481.2	1632/12/11–18	N	61 27.1	17.102	17.064	–27.2	–23.1	6	61 27.8	17.095	17.198	–27.6	–23.1
2317510.8	1633/ 1/10– 4	N	61 16.6	17.045	16.854	–26.8	–21.9	–15	61 20.8	17.026	17.207	–27.8	–22.0
2317673.2	1633/ 6/21–20	F	61 13.0	16.835	17.227	–28.3	23.4	16	61 17.6	16.825	17.172	–27.9	23.4
2317702.7	1633/ 7/21– 2	F	61 25.0	16.901	16.440	–25.2	20.5	– 4	61 25.4	16.900	16.620	–25.9	20.5
2317894.7	1634/ 1/29– 6	N	61 27.6	17.095	15.589	–21.7	–17.9	4	61 27.9	17.097	15.422	–20.9	–17.8
2317924.2	1634/ 2/27–17	N	61 10.4	17.023	13.705	– 9.8	– 8.1	–19	61 16.0	16.994	14.289	–14.9	– 8.4

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2318086.6	1634/ 8/ 9– 2	F	61 12.4	16.880	14.889	–18.8	15.9	17	61 16.9	16.877	14.282	–14.7	15.7
2318116.1	1634/ 9/ 7–10	F	61 24.5	17.011	13.593	– 6.6	6.0	– 5	61 25.0	17.011	13.688	– 8.0	6.1
2318308.1	1635/ 3/18–19	N	61 25.1	17.067	13.446	0.6	– 0.8	1	61 25.2	17.067	13.451	1.2	– 0.8
2318337.6	1635/ 4/17– 3	N	61 5.6	16.903	14.130	13.8	10.3	–20	61 12.1	16.888	13.642	8.3	10.0
2318500.0	1635/ 9/26–12	F	61 16.1	16.975	13.470	3.7	– 1.2	15	61 20.1	16.955	13.718	8.2	– 1.5
2318529.6	1635/10/25–21	F	61 27.3	17.053	14.692	16.4	–12.2	– 6	61 28.0	17.054	14.476	14.9	–12.2
2318692.0	1636/ 4/ 5–20	N	60 59.6	16.899	13.812	10.3	6.5	23	61 8.4	16.894	14.585	16.3	6.8
2318721.5	1636/ 5/ 5– 4	N	61 24.7	16.948	15.614	21.1	16.3	1	61 24.7	16.949	15.657	21.3	16.4
2318751.0	1636/ 6/ 3–11	N	61 4.1	16.839	16.873	26.8	22.4	–21	61 11.0	16.813	16.422	25.0	22.3
2318913.5	1636/11/12–23	F	61 21.2	17.029	16.012	22.7	–18.1	13	61 24.3	17.022	16.503	24.6	–18.2
2318943.0	1636/12/12– 9	F	61 27.0	17.122	17.121	26.7	–23.1	– 8	61 28.2	17.112	17.088	26.5	–23.1
2319105.4	1637/ 5/24– 4	N	60 58.3	16.813	16.430	24.8	20.8	23	61 6.9	16.839	16.842	26.0	20.9
2319134.9	1637/ 6/22–11	N	61 22.0	16.953	16.852	25.6	23.4	1	61 22.0	16.953	16.835	25.5	23.4
2319164.5	1637/ 7/21–18	N	61 1.9	16.863	15.374	20.0	20.4	–21	61 8.9	16.876	16.145	23.3	20.5
2319326.9	1637/12/31–12	F	61 23.1	17.132	16.430	23.6	–23.0	11	61 25.3	17.127	16.130	22.2	–23.0
2319356.4	1638/ 1/29–22	F	61 23.4	17.096	14.886	15.6	–17.7	–11	61 25.4	17.097	15.262	17.9	–17.8
2319518.8	1638/ 7/11–11	N	60 58.0	16.838	15.734	21.0	22.1	23	61 6.7	16.826	15.070	17.1	22.0
2319548.4	1638/ 8/ 9–18	N	61 23.3	16.963	14.595	12.6	15.7	2	61 23.3	16.961	14.566	12.3	15.7
2319577.9	1638/ 9/ 8– 2	N	61 3.8	16.880	13.783	1.4	5.8	–21	61 10.9	16.898	14.023	6.7	6.1
2319740.3	1639/ 2/18– 1	F	61 26.0	17.071	14.259	7.5	–11.7	8	61 27.4	17.061	14.150	5.4	–11.6
2319769.8	1639/ 3/19–10	F	61 21.1	16.974	14.078	– 4.0	– 0.6	–13	61 23.9	16.963	14.031	– 0.8	– 0.8
2319932.3	1639/ 8/28–19	N	61 1.7	16.852	14.040	5.1	9.6	22	61 9.9	16.815	13.987	– 0.3	9.3
2319961.8	1639/ 9/27– 3	N	61 26.3	17.007	14.285	– 5.8	– 1.5	0	61 26.3	17.007	14.292	– 5.9	– 1.5
2319991.3	1639/10/26–12	N	61 3.2	16.994	15.057	–15.4	–12.5	–22	61 11.1	16.973	14.600	–11.3	–12.2
2320153.7	1640/ 4/ 6–11	F	61 24.2	16.996	14.678	–10.0	6.7	7	61 25.2	17.002	14.830	–11.5	6.8
2320183.3	1640/ 5/ 5–19	F	61 16.1	16.936	15.643	–17.8	16.5	–14	61 19.5	16.921	15.337	–15.7	16.4
2320345.7	1640/10/15– 4	N	61 4.5	16.965	14.699	–11.1	– 8.7	21	61 11.8	16.948	15.195	–14.7	– 9.0
2320375.2	1640/11/13–14	N	61 26.9	17.120	15.880	–18.2	–18.2	– 1	61 26.9	17.121	15.857	–18.0	–18.2
2320404.8	1640/12/13– 1	N	60 59.2	17.020	16.098	–20.5	–23.2	–24	61 8.6	16.997	16.078	–20.0	–23.1
2320567.2	1641/ 5/24–20	F	61 22.5	16.947	16.059	–19.0	20.9	7	61 23.4	16.945	16.141	–19.3	21.0
2320596.7	1641/ 6/23– 3	F	61 15.2	16.857	16.081	–19.4	23.4	–14	61 18.7	16.860	16.184	–19.8	23.4
2320759.1	1641/12/ 2–17	N	61 11.1	17.054	16.003	–18.9	–22.1	18	61 16.9	17.019	16.123	–19.3	–22.2
2320788.7	1642/ 1/ 1– 3	N	61 28.8	17.095	16.031	–18.2	–23.0	– 3	61 29.1	17.095	16.076	–18.5	–23.0
2320980.6	1642/ 7/12– 3	F	61 23.8	16.884	15.818	–17.0	22.0	7	61 24.6	16.881	15.716	–16.4	22.0
2321010.1	1642/ 8/10–10	F	61 16.3	16.893	15.008	–11.4	15.6	–14	61 19.7	16.887	15.284	–13.5	15.7
2321172.5	1643/ 1/20– 6	N	61 15.2	17.047	15.546	–15.6	–20.1	15	61 19.6	17.038	15.304	–13.6	–20.0
2321202.1	1643/ 2/18–16	N	61 25.8	17.085	14.859	– 8.7	–11.5	– 6	61 26.4	17.078	14.952	– 9.7	–11.6
2321394.0	1643/ 8/29–10	F	61 23.6	16.976	14.779	– 7.7	9.4	7	61 24.4	16.976	14.706	– 6.4	9.3
2321423.6	1643/ 9/27–19	F	61 15.4	17.005	14.465	1.1	– 1.8	–15	61 19.2	17.008	14.503	– 1.8	– 1.5
2321586.0	1644/ 3/ 8–18	N	61 15.1	17.050	14.539	– 4.6	– 4.4	14	61 18.6	17.051	14.487	– 1.9	– 4.2
2321615.5	1644/ 4/ 7– 3	N	61 21.9	17.007	14.577	4.5	7.0	– 8	61 22.8	17.005	14.536	3.0	6.9
2321807.5	1644/10/15–20	F	61 27.5	17.047	14.623	5.5	– 9.0	6	61 28.0	17.042	14.687	6.6	– 9.0
2321837.0	1644/11/14– 6	F	61 16.5	17.032	15.233	13.7	–18.4	–16	61 21.0	17.020	14.973	11.1	–18.2
2321999.4	1645/ 4/26– 4	N	61 16.0	16.931	14.715	9.1	13.6	13	61 19.0	16.934	14.960	11.4	13.7
2322028.9	1645/ 5/25–11	N	61 20.9	16.917	15.577	16.2	21.0	– 8	61 22.0	16.908	15.424	15.1	21.0

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2322220.9	1645/12/ 3– 8	F	61 30.3	17.104	15.850	17.8	–22.2	4	61 30.6	17.105	15.922	18.2	–22.2
2322250.4	1646/ 1/ 1–19	F	61 12.6	17.076	16.205	20.4	–22.9	–19	61 18.5	17.047	16.177	20.1	–23.0
2322412.8	1646/ 6/13–11	N	61 13.9	16.896	16.039	19.9	23.2	13	61 16.8	16.907	16.234	20.8	23.2
2322442.4	1646/ 7/12–18	N	61 18.6	16.949	16.290	20.9	21.9	– 8	61 19.7	16.949	16.343	21.1	22.0
2322604.8	1646/12/22–10	F	61 1.5	17.024	16.177	21.5	–23.4	24	61 10.8	17.003	16.349	21.9	–23.4
2322634.3	1647/ 1/20–21	F	61 29.6	17.150	16.258	20.8	–20.0	1	61 29.6	17.150	16.240	20.7	–20.0
2322663.8	1647/ 2/19– 8	F	61 6.9	16.976	14.943	14.3	–11.3	–21	61 14.2	16.967	15.540	17.8	–11.6
2322826.3	1647/ 7/31–19	N	61 14.6	16.934	15.960	20.4	18.2	13	61 17.5	16.917	15.646	18.7	18.1
2322855.8	1647/ 8/30– 2	N	61 20.6	16.955	14.804	13.0	9.2	– 8	61 21.8	16.965	15.026	14.7	9.3
2323018.2	1648/ 2/ 9– 0	F	61 7.2	17.024	15.398	18.4	–14.8	21	61 14.8	16.988	14.839	14.5	–14.5
2323047.7	1648/ 3/ 9–10	F	61 29.7	17.035	14.324	8.7	– 4.2	– 1	61 29.7	17.036	14.344	8.9	– 4.2
2323077.3	1648/ 4/ 7–18	F	61 3.2	16.863	13.812	– 2.9	7.2	–23	61 11.8	16.825	13.871	3.0	6.9
2323239.7	1648/ 9/17– 3	N	61 18.5	16.953	14.012	6.7	2.1	12	61 21.1	16.939	13.890	3.4	1.9
2323269.2	1648/10/16–11	N	61 22.3	17.041	13.946	– 5.4	– 9.2	– 9	61 23.8	17.037	13.870	– 3.0	– 9.1
2323431.6	1649/ 3/28–11	F	61 8.1	16.931	13.644	0.8	3.2	19	61 14.7	16.936	13.782	– 4.5	3.5
2323461.2	1649/ 4/26–19	F	61 26.0	16.986	14.319	–11.4	13.8	– 2	61 26.1	16.984	14.266	–10.9	13.8
2323490.7	1649/ 5/26– 3	F	60 58.4	16.818	15.564	–21.1	21.1	–24	61 7.7	16.800	14.779	–16.3	21.0
2323653.1	1649/11/ 4–13	N	61 20.8	17.075	14.529	–14.4	–15.6	11	61 22.8	17.071	14.913	–16.9	–15.7
2323682.6	1649/12/ 4– 0	N	61 20.7	17.111	16.257	–23.7	–22.3	–11	61 23.0	17.109	15.875	–22.0	–22.2
2323845.1	1650/ 5/15–20	F	61 6.9	16.886	15.191	–19.7	19.0	19	61 13.2	16.890	15.996	–23.2	19.2
2323874.6	1650/ 6/14– 3	F	61 24.8	16.926	16.902	–26.3	23.3	– 2	61 24.8	16.927	16.850	–26.1	23.2
2323904.1	1650/ 7/13–10	F	60 58.6	16.763	16.689	–26.3	21.8	–24	61 7.9	16.770	17.013	–27.2	22.0
2324066.5	1650/12/23– 3	N	61 25.6	17.101	17.225	–27.5	–23.4	8	61 26.8	17.091	17.260	–27.6	–23.4
2324096.1	1651/ 1/21–13	N	61 19.7	17.049	16.349	–24.7	–19.8	–14	61 22.8	17.035	16.820	–26.3	–19.9
2324258.5	1651/ 7/ 3– 3	F	61 8.5	16.812	17.084	–27.8	23.0	19	61 14.6	16.795	16.728	–26.4	22.9
2324288.0	1651/ 8/ 1–10	F	61 26.2	16.913	15.869	–22.7	18.1	– 2	61 26.3	16.913	15.958	–23.1	18.1
2324317.6	1651/ 8/30–17	F	60 59.0	16.852	13.899	–12.2	8.9	–24	61 8.6	16.843	14.821	–18.4	9.3
2324480.0	1652/ 2/ 9–15	N	61 26.0	17.081	14.938	–18.4	–14.6	6	61 26.7	17.084	14.704	–17.0	–14.5
2324509.5	1652/ 3/10– 1	N	61 13.7	17.023	13.469	– 5.6	– 3.9	–16	61 18.0	16.999	13.808	–10.3	– 4.2
2324671.9	1652/ 8/19–10	F	61 8.4	16.870	14.314	–15.4	12.6	19	61 14.4	16.863	13.764	–10.2	12.3
2324701.5	1652/ 9/17–18	F	61 26.0	17.033	13.441	– 2.4	1.8	– 2	61 26.2	17.033	13.460	– 3.2	1.9
2324893.4	1653/ 3/29– 3	N	61 23.7	17.049	13.508	4.9	3.5	4	61 24.1	17.050	13.569	6.1	3.6
2324922.9	1653/ 4/27–11	N	61 9.6	16.910	14.660	17.5	14.0	–17	61 14.6	16.899	14.067	13.0	13.8
2325085.4	1653/10/ 6–20	F	61 12.7	16.975	13.607	7.9	– 5.5	18	61 18.0	16.951	14.094	13.0	– 5.8
2325114.9	1653/11/ 5– 5	F	61 29.1	17.074	15.292	20.1	–15.8	– 4	61 29.4	17.075	15.127	19.2	–15.8
2325306.8	1654/ 5/16–12	N	61 23.6	16.933	16.199	24.0	19.2	3	61 23.8	16.935	16.342	24.6	19.2
2325336.4	1654/ 6/14–18	N	61 8.7	16.857	17.121	27.8	23.3	–17	61 13.9	16.838	16.964	27.1	23.2
2325498.8	1654/11/24– 7	F	61 18.2	17.029	16.566	25.4	–20.6	16	61 22.4	17.019	17.002	26.8	–20.8
2325528.3	1654/12/23–18	F	61 28.7	17.129	17.125	27.0	–23.4	– 7	61 29.4	17.122	17.204	27.2	–23.4
2325720.3	1655/ 7/ 3–18	N	61 21.3	16.948	16.619	25.2	22.9	4	61 21.6	16.949	16.509	24.7	22.9
2325749.8	1655/ 8/ 2– 2	N	61 6.9	16.900	14.881	17.6	17.9	–18	61 12.2	16.913	15.601	21.3	18.1
2325912.2	1656/ 1/11–20	F	61 20.3	17.120	15.977	22.3	–21.7	14	61 23.4	17.113	15.524	20.0	–21.6
2325941.7	1656/ 2/10– 7	F	61 25.3	17.094	14.379	12.4	–14.4	– 9	61 26.6	17.096	14.652	14.5	–14.5
2326133.7	1656/ 8/20– 2	N	61 23.2	16.975	14.161	9.2	12.3	4	61 23.4	16.969	14.089	8.3	12.3
2326163.2	1656/ 9/18–10	N	61 9.0	16.922	13.738	– 2.8	1.6	–18	61 14.5	16.936	13.769	2.0	1.9

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2326325.6	1657/ 2/28– 9	F	61 23.2	17.047	13.943	3.5	– 7.7	11	61 25.3	17.035	13.907	0.7	– 7.5
2326355.2	1657/ 3/29–18	F	61 23.3	16.969	14.219	– 8.3	3.7	–10	61 25.2	16.960	14.071	– 5.7	3.6
2326547.1	1657/10/ 7–11	N	61 26.5	17.020	14.480	–10.1	– 5.7	3	61 26.6	17.019	14.542	–10.7	– 5.8
2326576.6	1657/11/ 5–21	N	61 8.3	17.031	15.586	–19.0	–16.0	–20	61 14.7	17.008	15.090	–15.8	–15.8
2326739.1	1658/ 4/17–19	F	61 21.4	16.965	15.001	–14.1	10.7	10	61 23.2	16.973	15.269	–15.9	10.9
2326768.6	1658/ 5/17– 3	F	61 19.0	16.939	16.107	–20.6	19.3	–12	61 21.2	16.927	15.872	–19.4	19.2
2326931.0	1658/10/26–13	N	61 0.0	16.960	15.044	–15.0	–12.6	23	61 9.0	16.938	15.675	–18.5	–13.0
2326960.5	1658/11/24–23	N	61 27.3	17.130	16.282	–20.7	–20.8	1	61 27.4	17.130	16.295	–20.8	–20.8
2326990.1	1658/12/24–10	N	61 4.2	17.040	16.084	–20.7	–23.4	–22	61 12.0	17.021	16.309	–21.5	–23.4
2327152.5	1659/ 6/ 5– 3	F	61 20.1	16.927	16.280	–20.6	22.5	10	61 21.7	16.924	16.305	–20.7	22.6
2327182.0	1659/ 7/ 4–10	F	61 18.6	16.876	15.933	–18.9	22.9	–11	61 20.9	16.880	16.126	–19.8	22.9
2327344.4	1659/12/14– 2	N	61 7.1	17.046	16.111	–20.0	–23.2	20	61 14.3	17.004	16.033	–19.3	–23.3
2327374.0	1660/ 1/12–12	N	61 29.4	17.095	15.739	–16.9	–21.6	– 1	61 29.4	17.095	15.771	–17.1	–21.6
2327403.5	1660/ 2/10–23	N	61 0.3	16.959	14.605	– 9.6	–14.2	–25	61 9.8	16.909	15.125	–13.7	–14.5
2327565.9	1660/ 7/22–10	F	61 21.8	16.880	15.471	–15.2	20.1	10	61 23.4	16.874	15.295	–13.9	20.1
2327595.5	1660/ 8/20–17	F	61 19.9	16.923	14.691	– 8.0	12.1	–11	61 22.2	16.919	14.881	–10.1	12.3
2327757.9	1661/ 1/30–14	N	61 11.1	17.026	15.124	–12.9	–17.4	18	61 16.7	17.015	14.855	–10.0	–17.2
2327787.4	1661/ 3/ 1– 0	N	61 26.3	17.074	14.604	– 4.7	– 7.5	– 4	61 26.5	17.070	14.639	– 5.4	– 7.5
2327979.3	1661/ 9/ 8–18	F	61 22.0	16.982	14.560	– 3.6	5.4	9	61 23.5	16.981	14.528	– 1.8	5.2
2328008.9	1661/10/ 8– 3	F	61 19.2	17.041	14.610	5.4	– 6.0	–12	61 21.9	17.042	14.544	3.0	– 5.8
2328171.3	1662/ 3/20– 2	N	61 10.8	17.016	14.430	– 0.3	– 0.1	17	61 15.6	17.020	14.502	3.0	0.2
2328200.8	1662/ 4/18–11	N	61 22.9	17.000	14.830	8.4	11.0	– 5	61 23.3	16.999	14.765	7.5	10.9
2328392.8	1662/10/27– 5	F	61 26.5	17.059	14.907	9.4	–12.9	8	61 27.5	17.051	15.040	10.7	–13.0
2328422.3	1662/11/25–15	F	61 20.3	17.057	15.647	16.1	–20.9	–14	61 23.7	17.046	15.434	14.4	–20.8
2328584.7	1663/ 5/ 7–12	N	61 11.9	16.898	15.052	12.3	16.8	15	61 16.2	16.901	15.377	14.6	17.0
2328614.3	1663/ 6/ 5–19	N	61 22.4	16.915	15.896	17.7	22.6	– 6	61 22.9	16.911	15.820	17.2	22.6
2328806.2	1663/12/14–17	F	61 29.4	17.106	16.109	18.8	–23.2	5	61 30.0	17.107	16.173	19.1	–23.3
2328835.7	1664/ 1/13– 4	F	61 16.4	17.086	16.041	19.0	–21.5	–17	61 21.0	17.063	16.185	19.6	–21.6
2328998.2	1664/ 6/23–19	N	61 10.0	16.873	16.127	20.1	23.4	16	61 14.3	16.883	16.198	20.2	23.4
2329027.7	1664/ 7/23– 2	N	61 20.5	16.963	16.005	19.0	20.0	– 6	61 21.1	16.964	16.086	19.3	20.0
2329219.6	1665/ 1/31– 6	F	61 28.8	17.140	15.810	18.0	–17.2	3	61 29.0	17.139	15.743	17.6	–17.2
2329249.2	1665/ 3/ 1–16	F	61 10.9	16.979	14.617	10.2	– 7.2	–19	61 16.9	16.974	15.056	13.8	– 7.5
2329411.6	1665/ 8/11– 2	N	61 11.4	16.927	15.467	17.3	15.2	16	61 15.6	16.905	15.101	14.7	15.0
2329441.1	1665/ 9/ 9–10	N	61 23.0	16.980	14.518	8.9	5.1	– 6	61 23.6	16.988	14.627	10.1	5.2
2329603.5	1666/ 2/19– 8	F	61 1.8	16.987	14.872	14.6	–11.1	24	61 11.1	16.950	14.398	9.8	–10.8
2329633.1	1666/ 3/20–18	F	61 29.1	17.018	14.180	4.4	0.2	1	61 29.1	17.018	14.170	4.1	0.2
2329662.6	1666/ 4/19– 2	F	61 7.9	16.871	14.114	– 6.8	11.2	–20	61 14.8	16.839	13.974	– 1.8	10.9
2329825.0	1666/ 9/28–11	N	61 15.8	16.955	13.931	2.4	– 2.2	15	61 19.5	16.937	13.942	– 1.4	– 2.4
2329854.5	1666/10/27–20	N	61 24.8	17.062	14.315	– 9.2	–13.1	– 7	61 25.7	17.059	14.198	– 7.6	–13.0
2330017.0	1667/ 4/.8–19	F	61 2.5	16.885	13.753	– 3.3	7.4	22	61 10.9	16.894	14.123	– 9.1	7.7
2330046.5	1667/ 5/ 8– 3	F	61 25.7	16.970	14.795	–14.5	17.0	0	61 25.7	16.970	14.809	–14.6	17.0
2330076.0	1667/ 6/ 6–10	F	61 3.7	16.841	16.039	–22.5	22.7	–21	61 11.1	16.829	15.422	–19.3	22.6
2330238.4	1667/11/15–22	N	61 18.6	17.078	15.063	–17.4	–18.7	13	61 21.4	17.071	15.545	–20.0	–18.8
2330268.0	1667/12/15– 9	N	61 23.3	17.123	16.650	–24.7	–23.3	– 9	61 24.8	17.122	16.430	–23.8	–23.3
2330430.4	1668/ 5/26– 3	F	61 1.5	16.843	15.679	–21.8	21.2	23	61 9.7	16.847	16.471	–24.9	21.4

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2330459.9	1668/ 6/24–11	F	61 24.9	16.927	17.030	–26.3	23.4	0	61 24.9	16.926	17.034	–26.4	23.4
2330489.4	1668/ 7/23–18	F	61 4.3	16.801	16.290	–24.3	19.9	–22	61 11.7	16.810	16.837	–26.1	20.0
2330651.9	1669/ 1/ 2–11	N	61 23.5	17.097	17.108	–26.9	–22.8	11	61 25.4	17.083	16.982	–26.4	–22.8
2330681.4	1669/ 1/31–22	N	61 22.2	17.049	15.752	–21.8	–17.0	–12	61 24.5	17.039	16.215	–23.7	–17.1
2330843.8	1669/ 7/13–11	F	61 3.4	16.788	16.722	–26.5	21.8	22	61 11.4	16.765	16.077	–23.8	21.6
2330873.3	1669/ 8/11–17	F	61 26.7	16.925	15.279	–19.6	15.0	1	61 26.7	16.925	15.257	–19.5	15.0
2330902.9	1669/ 9/10– 1	F	61 4.9	16.901	13.638	– 8.2	4.8	–21	61 12.5	16.890	14.249	–14.0	5.2
2331065.3	1670/ 2/20– 0	N	61 23.8	17.063	14.373	–14.6	–10.9	8	61 25.0	17.067	14.123	–12.5	–10.7
2331094.8	1670/ 3/21– 9	N	61 16.6	17.021	13.401	– 1.3	0.4	–13	61 19.7	17.002	13.532	– 5.4	0.2
2331257.2	1670/ 8/30–18	F	61 3.8	16.858	13.844	–11.6	8.8	22	61 11.5	16.849	13.445	– 5.3	8.4
2331286.8	1670/ 9/29– 2	F	61 27.0	17.052	13.451	1.8	– 2.4	0	61 27.0	17.052	13.450	1.8	– 2.4
2331316.3	1670/10/28–12	F	61 2.7	16.994	14.249	15.2	–13.3	–22	61 11.2	16.987	13.657	9.0	–13.0
2331478.7	1671/ 4/ 9–11	N	61 21.7	17.027	13.732	9.0	7.7	7	61 22.6	17.030	13.905	10.9	7.8
2331508.3	1671/ 5/ 8–19	N	61 13.1	16.915	15.272	20.7	17.2	–15	61 16.8	16.909	14.674	17.3	17.0
2331670.7	1671/10/18– 4	F	61 8.9	16.973	13.906	12.0	– 9.6	20	61 15.6	16.945	14.656	17.4	– 9.9
2331700.2	1671/11/16–14	F	61 30.3	17.091	15.949	23.2	–18.9	– 2	61 30.4	17.091	15.870	22.8	–18.8
2331729.7	1671/12/16– 0	F	61 1.2	16.990	17.114	28.2	–23.3	–24	61 11.0	16.948	16.713	26.6	–23.3
2331892.2	1672/ 5/26–19	N	61 21.9	16.917	16.723	26.2	21.3	6	61 22.6	16.919	16.921	26.9	21.4
2331921.7	1672/ 6/25– 2	N	61 12.7	16.873	17.137	27.9	23.4	–15	61 16.5	16.862	17.245	28.1	23.4
2332084.1	1672/12/ 4–16	F	61 14.7	17.026	16.990	27.2	–22.4	18	61 20.1	17.011	17.234	27.8	–22.5
2332113.6	1673/ 1/ 3– 3	F	61 29.9	17.131	16.860	26.3	–22.8	– 5	61 30.2	17.127	16.981	26.7	–22.8
2332305.6	1673/ 7/14– 2	N	61 20.1	16.943	16.196	23.9	21.7	6	61 20.8	16.944	15.949	22.9	21.6
2332335.1	1673/ 8/12– 9	N	61 11.3	16.934	14.385	14.6	14.8	–15	61 15.2	16.946	14.961	18.2	15.0
2332497.5	1674/ 1/22– 5	F	61 16.9	17.103	15.388	20.1	–19.6	15	61 21.0	17.092	14.837	16.8	–19.4
2332527.1	1674/ 2/20–16	F	61 26.7	17.088	13.952	8.6	–10.6	– 7	61 27.4	17.090	14.109	10.5	–10.7
2332719.0	1674/ 8/31–10	N	61 22.5	16.985	13.816	5.5	8.5	6	61 23.1	16.975	13.750	3.8	8.4
2332748.5	1674/ 9/29–18	N	61 13.7	16.960	13.846	– 7.1	– 2.7	–15	61 17.7	16.970	13.705	– 2.9	– 2.5
2332911.0	1675/ 3/11–18	F	61 19.8	17.017	13.764	– 0.7	– 3.5	13	61 22.9	17.004	13.860	– 4.2	– 3.3
2332940.5	1675/ 4/10– 2	F	61 25.1	16.961	14.516	–12.5	7.9	– 8	61 26.2	16.955	14.316	–10.5	7.8
2333132.4	1675/10/18–19	N	61 26.2	17.031	14.826	–14.2	– 9.9	5	61 26.6	17.029	14.980	–15.3	– 9.9
2333162.0	1675/11/17– 5	N	61 12.8	17.060	16.140	–22.1	–19.0	–17	61 17.8	17.039	15.701	–19.8	–18.9
2333324.4	1676/ 4/28– 3	F	61 18.1	16.932	15.425	–17.8	14.3	12	61 20.8	16.942	15.802	–19.7	14.5
2333353.9	1676/ 5/27–10	F	61 21.2	16.940	16.501	–22.8	21.4	– 8	61 22.5	16.932	16.377	–22.3	21.4
2333545.9	1676/12/ 5– 8	N	61 27.2	17.136	16.558	–22.4	–22.5	3	61 27.4	17.135	16.568	–22.5	–22.5
2333575.4	1677/ 1/ 3–19	N	61 8.6	17.054	15.864	–20.0	–22.7	–20	61 15.0	17.040	16.283	–21.7	–22.8
2333737.8	1677/ 6/15–11	F	61 17.1	16.907	16.339	–21.5	23.3	12	61 19.8	16.901	16.234	–20.9	23.3
2333767.3	1677/ 7/14–18	F	61 21.4	16.894	15.632	–17.7	21.5	– 9	61 22.7	16.900	15.843	–18.8	21.6
2333929.8	1677/12/24–10	N	61 2.5	17.033	16.021	–20.2	–23.4	23	61 11.2	16.984	15.709	–18.2	–23.4
2333959.3	1678/ 1/22–21	N	61 29.3	17.091	15.327	–14.8	–19.4	0	61 29.3	17.091	15.319	–14.7	–19.4
2333988.8	1678/ 2/21– 7	N	61 4.9	16.964	14.313	– 5.8	–10.4	–22	61 12.7	16.922	14.692	–10.3	–10.7
2334151.2	1678/ 8/ 2–18	F	61 19.1	16.875	15.057	–12.8	17.6	12	61 21.7	16.865	14.838	–10.6	17.5
2334180.8	1678/ 9/ 1– 1	F	61 23.0	16.952	14.448	– 4.2	8.3	– 9	61 24.4	16.949	14.540	– 6.0	8.4
2334343.2	1679/ 2/10–23	N	61 6.3	16.999	14.700	– 9.6	–14.0	20	61 13.4	16.988	14.485	– 5.7	–13.8
2334372.7	1679/ 3/12– 9	N	61 26.3	17.061	14.472	– 0.4	– 3.2	– 2	61 26.3	17.059	14.473	– 0.8	– 3.2
2334402.3	1679/ 4/10–18	N	60 57.8	16.906	14.600	8.7	8.2	–24	61 7.1	16.872	14.404	4.1	7.8

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2334564.7	1679/ 9/20– 2	F	61 20.0	16.985	14.465	0.6	1.1	12	61 22.3	16.984	14.521	3.0	0.9
2334594.2	1679/10/19–11	F	61 22.4	17.072	14.881	9.5	–10.1	–10	61 24.2	17.071	14.759	7.7	–10.0
2334756.6	1680/ 3/30–10	N	61 6.0	16.976	14.456	4.0	4.2	20	61 12.3	16.984	14.687	7.6	4.5
2334786.2	1680/ 4/28–19	N	61 23.3	16.992	15.169	12.1	14.6	– 3	61 23.4	16.991	15.124	11.6	14.5
2334978.1	1680/11/ 6–13	F	61 24.9	17.067	15.264	12.8	–16.4	10	61 26.6	17.056	15.455	14.2	–16.5
2335007.6	1680/12/ 5–23	F	61 23.6	17.075	15.964	17.7	–22.6	–11	61 26.0	17.068	15.844	16.9	–22.5
2335170.0	1681/ 5/17–19	N	61 7.2	16.863	15.391	15.0	19.6	19	61 13.0	16.865	15.731	16.9	19.7
2335199.6	1681/ 6/16– 2	N	61 23.3	16.914	16.074	18.4	23.4	– 3	61 23.4	16.912	16.057	18.3	23.4
2335391.5	1681/12/25– 2	F	61 28.0	17.103	16.183	19.0	–23.4	7	61 29.0	17.103	16.192	18.9	–23.4
2335421.1	1682/ 1/23–12	F	61 19.6	17.090	15.734	16.8	–19.3	–14	61 23.1	17.073	15.966	18.0	–19.4
2335583.5	1682/ 7/ 5– 2	N	61 5.6	16.849	16.036	19.4	22.8	19	61 11.5	16.856	15.939	18.6	22.7
2335613.0	1682/ 8/ 3– 9	N	61 21.9	16.975	15.634	16.3	17.4	– 3	61 22.0	16.976	15.687	16.6	17.4
2335805.0	1683/ 2/11–15	F	61 27.4	17.126	15.350	14.6	–13.8	5	61 27.9	17.123	15.243	13.8	–13.7
2335834.5	1683/ 3/13– 1	F	61 14.5	16.980	14.425	5.9	– 2.9	–17	61 19.2	16.977	14.689	9.3	– 3.2
2335996.9	1683/ 8/22–10	N	61 7.6	16.920	15.007	13.7	11.7	18	61 13.3	16.891	14.668	10.3	11.5
2336026.4	1683/ 9/20–18	N	61 24.8	17.003	14.370	4.6	0.9	– 3	61 25.0	17.007	14.403	5.3	0.9
2336218.4	1684/ 3/31– 2	F	61 27.8	16.998	14.192	0.1	4.4	4	61 28.1	16.998	14.196	– 0.8	4.5
2336247.9	1684/ 4/29–10	F	61 12.1	16.877	14.514	–10.3	14.8	–18	61 17.4	16.851	14.256	– 6.3	14.5
2336410.3	1684/10/ 8–19	N	61 12.6	16.956	14.001	– 1.8	– 6.4	17	61 17.5	16.933	14.178	– 6.0	– 6.7
2336439.9	1684/11/ 7– 4	N	61 26.7	17.079	14.774	–12.6	–16.5	– 4	61 27.1	17.076	14.667	–11.6	–16.5
2336631.8	1685/ 5/18–11	F	61 24.8	16.952	15.286	–17.1	19.7	3	61 25.0	16.955	15.382	–17.7	19.7
2336661.3	1685/ 6/16–18	F	61 8.4	16.864	16.355	–23.1	23.4	–19	61 14.1	16.856	15.971	–21.3	23.4
2336823.8	1685/11/26– 7	N	61 15.8	17.077	15.582	–19.8	–21.1	15	61 19.6	17.068	16.088	–22.0	–21.2
2336853.3	1685/12/25–18	N	61 25.2	17.131	16.811	–24.7	–23.4	– 7	61 26.1	17.130	16.738	–24.4	–23.4
2337045.2	1686/ 7/ 5–18	F	61 24.5	16.927	16.931	–25.6	22.7	3	61 24.7	16.925	16.911	–25.5	22.7
2337074.8	1686/ 8/ 4– 1	F	61 9.5	16.839	15.803	–21.6	17.2	–18	61 15.1	16.849	16.406	–24.0	17.4
2337237.2	1687/ 1/13–20	N	61 20.8	17.087	16.746	–25.4	–21.3	13	61 23.5	17.070	16.443	–24.1	–21.2
2337266.7	1687/ 2/12– 6	N	61 24.2	17.046	15.166	–18.3	–13.6	– 9	61 25.8	17.039	15.537	–20.2	–13.7
2337458.7	1687/ 8/23– 1	F	61 26.7	16.936	14.745	–16.1	11.5	3	61 26.8	16.935	14.637	–15.3	11.5
2337488.2	1687/ 9/21– 9	F	61 10.2	16.947	13.529	– 3.9	0.6	–18	61 16.1	16.934	13.860	– 9.2	0.9
2337650.6	1688/ 3/ 2– 8	N	61 21.0	17.040	13.950	–10.5	– 6.8	11	61 22.9	17.046	13.742	– 7.6	– 6.6
2337680.1	1688/ 3/31–17	N	61 18.9	17.017	13.499	2.9	4.7	–11	61 21.1	17.001	13.476	– 0.4	4.5
2337872.1	1688/10/ 9–11	F	61 27.3	17.068	13.625	6.1	– 6.7	2	61 27.4	17.068	13.661	6.7	– 6.7
2337901.6	1688/11/ 7–21	F	61 8.0	17.032	14.867	18.7	–16.8	–20	61 14.8	17.024	14.176	13.7	–16.5
2338064.0	1689/ 4/19–19	N	61 19.1	17.002	14.101	12.9	11.6	9	61 20.7	17.006	14.427	15.4	11.7
2338093.6	1689/ 5/19– 3	N	61 16.1	16.920	15.899	23.4	19.9	–13	61 18.6	16.917	15.388	21.0	19.7
2338256.0	1689/10/28–12	F	61 4.6	16.969	14.350	15.9	–13.5	23	61 12.9	16.934	15.340	21.2	–13.8
2338285.5	1689/11/26–23	F	61 30.9	17.103	16.569	25.6	–21.2	0	61 30.9	17.103	16.578	25.6	–21.2
2338315.1	1689/12/26– 9	F	61 6.3	17.009	17.152	28.3	–23.3	–22	61 14.4	16.974	17.162	28.0	–23.4
2338477.5	1690/ 6/ 7– 3	N	61 19.6	16.900	17.104	27.7	22.8	9	61 21.0	16.901	17.265	28.2	22.8
2338507.0	1690/ 7/ 6– 9	N	61 16.2	16.890	16.918	27.2	22.6	–12	61 18.7	16.883	17.199	28.0	22.7
2338669.4	1690/12/16– 1	F	61 10.7	17.019	17.193	28.2	–23.3	20	61 17.4	16.998	17.122	27.7	–23.4
2338699.0	1691/ 1/14–11	F	61 30.5	17.128	16.372	24.7	–21.2	– 2	61 30.6	17.126	16.462	25.1	–21.2
2338890.9	1691/ 7/25– 9	N	61 18.2	16.938	15.642	21.9	19.6	10	61 19.7	16.938	15.261	20.1	19.5
2338920.4	1691/ 8/23–17	N	61 15.2	16.966	13.949	11.2	11.3	–12	61 17.8	16.976	14.341	14.5	11.4

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2339082.9	1692/ 2/ 2–14	F	61 12.9	17.079	14.754	17.3	–16.7	17	61 18.2	17.066	14.192	12.9	–16.5
2339112.4	1692/ 3/ 3– 0	F	61 27.5	17.079	13.651	4.6	– 6.5	– 4	61 27.8	17.080	13.712	5.9	– 6.6
2339304.3	1692/ 9/10–18	N	61 21.2	16.994	13.596	1.5	4.4	8	61 22.5	16.980	13.598	– 1.0	4.3
2339333.9	1692/10/10– 2	N	61 17.7	16.993	14.118	–11.3	– 6.9	–12	61 20.6	17.000	13.857	– 7.9	– 6.7
2339496.3	1693/ 3/22– 2	F	61 15.7	16.983	13.741	– 5.0	0.9	15	61 20.1	16.969	14.027	– 9.2	1.1
2339525.8	1693/ 4/20–10	F	61 26.3	16.952	14.952	–16.5	11.8	– 6	61 26.8	16.947	14.761	–15.2	11.7
2339717.8	1693/10/29– 4	N	61 25.3	17.039	15.304	–18.1	–13.7	7	61 26.2	17.036	15.563	–19.5	–13.8
2339747.3	1693/11/27–14	N	61 16.8	17.083	16.627	–24.4	–21.3	–15	61 20.5	17.064	16.331	–23.1	–21.2
2339909.7	1694/ 5/ 9–11	F	61 14.1	16.896	15.899	–21.0	17.5	15	61 18.1	16.908	16.330	–22.8	17.7
2339939.2	1694/ 6/ 7–18	F	61 22.9	16.940	16.753	–24.3	22.8	– 6	61 23.5	16.935	16.735	–24.2	22.8
2340131.2	1694/12/16–17	N	61 26.5	17.138	16.634	–23.3	–23.4	5	61 27.0	17.137	16.585	–23.1	–23.4
2340160.7	1695/ 1/15– 3	N	61 12.6	17.063	15.479	–18.4	–21.1	–17	61 17.6	17.053	15.994	–20.9	–21.2
2340323.1	1695/ 6/26–18	F	61 13.5	16.886	16.208	–21.6	23.3	16	61 17.4	16.877	15.923	–20.1	23.3
2340352.7	1695/ 7/26– 1	F	61 23.6	16.913	15.226	–15.7	19.5.	– 6	61 24.2	16.918	15.393	–16.8	19.5
2340544.6	1696/ 2/ 3– 6	N	61 28.6	17.083	14.871	–11.9	–16.5	2	61 28.7	17.082	14.820	–11.5	–16.5
2340574.1	1696/ 3/ 3–16	N	61 9.0	16.966	14.125	– 1.8	– 6.3	–20	61 15.4	16.932	14.325	– 6.2	– 6.6
2340736.6	1696/ 8/13– 1	F	61 16.0	16.870	14.637	– 9.7	14.5	15	61 19.8	16.855	14.435	– 6.6	14.3
2340766.1	1696/ 9/11– 9	F	61 25.4	16.978	14.315	– 0.1	4.2	– 6	61 26.1	16.975	14.330	– 1.5	4.3
2340928.5	1697/ 2/21– 8	N	61 1.0	16.965	14.338	– 5.9	–10.2	22	61 9.7	16.955	14.260	– 1.1	– 9.9
2340958.0	1697/ 3/22–17	N	61 25.7	17.044	14.477	3.9	1.1	1	61 25.7	17.045	14.482	4.1	1.1
2340987.6	1697/ 4/21– 2	N	61 2.5	16.917	14.957	12.6	12.0	–22	61 10.1	16.889	14.638	8.8	11.7
2341150.0	1697/ 9/30–10	F	61 17.4	16.987	14.504	5.0	– 3.1	14	61 20.7	16.985	14.686	7.7	– 3.4
2341179.5	1697/10/29–20	F	61 25.1	17.098	15.257	13.3	–13.9	– 8	61 26.1	17.097	15.125	12.1	–13.8
2341341.9	1698/ 4/10–18	N	61 0.6	16.930	14.611	8.2	8.3	22	61 8.6	16.943	15.011	11.9	8.6
2341371.5	1698/ 5/10– 3	N	61 23.2	16.982	15.549	15.2	17.7	– 1	61 23.2	16.982	15.546	15.2	17.7
2341401.0	1698/ 6/ 8–10	N	61 0.7	16.813	15.902	18.5	22.9	–22	61 8.6	16.810	15.765	17.4	22.8
2341563.4	1698/11/17–22	F	61 22.8	17.072	15.635	15.7	–19.3	12	61 25.3	17.057	15.840	16.9	–19.4
2341593.0	1698/12/17– 8	F	61 26.2	17.088	16.121	18.5	–23.4	– 9	61 27.9	17.084	16.103	18.3	–23.4
2341755.4	1699/ 5/29– 3	N	61 2.0	16.825	15.670	17.0	21.6	21	61 9.6	16.826	15.934	18.2	21.8
2341784.9	1699/ 6/27–10	N	61 23.6	16.913	16.084	18.3	23.3	0	61 23.6	16.913	16.084	18.3	23.3
2341814.4	1699/ 7/26–16	N	61 1.0	16.831	15.426	15.5	19.3	–21	61 8.9	16.829	15.795	17.4	19.5
2341976.8	1700/ 1/ 5–11	F	61 25.9	17.096	16.059	18.2	–22.6	9	61 27.6	17.095	15.982	17.7	–22.5
2342006.4	1700/ 2/ 3–21	F	61 22.2	17.090	15.361	13.9	–16.3	–12	61 24.8	17.077	15.597	15.4	–16.4
2342168.8	1700/ 7/16–10	N	61 0.7	16.826	15.785	18.0	21.4	21	61 8.4	16.828	15.530	16.1	21.2
2342198.3	1700/ 8/14–17	N	61 22.7	16.987	15.247	13.1	14.3	0	61 22.7	16.987	15.249	13.1	14.3
2342227.9	1700/ 9/13– 1	N	60 59.8	16.912	14.406	5.1	3.9	–22	61 8.0	16.934	14.735	9.3	4.2
2342390.3	1701/ 2/22–23	F	61 25.5	17.107	14.951	10.7	–10.0	8	61 26.5	17.103	14.837	9.4	– 9.9
2342419.8	1701/ 3/24– 9	F	61 17.7	16.979	14.378	1.6	1.4	–14	61 21.1	16.978	14.485	4.6	1.2
2342582.2	1701/ 9/ 2–18	N	61 3.3	16.910	14.635	9.8	7.9	21	61 10.7	16.875	14.398	5.6	7.5
2342611.8	1701/10/ 2– 2	N	61 26.0	17.023	14.365	0.3	– 3.4	– 1	61 26.0	17.024	14.366	0.5	– 3.4
2342641.3	1701/10/31–11	N	61 0.9	16.955	14.532	– 9.4	–14.1	–23	61 9.8	16.939	14.301	– 4.7	–13.8
2342803.7	1702/ 4/12–10	F	61 26.0	16.975	14.343	– 4.0	8.6	6	61 26.7	16.974	14.403	– 5.3	8.7
2342833.2	1702/ 5/11–18	F	61 15.8	16.882	14.966	–13.3	17.9	–15	61 19.7	16.861	14.673	–10.3	17.7
2342995.7	1702/10/21– 3	N	61 8.9	16.955	14.206	– 5.8	–10.5	20	61 15.2	16.927	14.557	–10.1	–10.8
2343025.2	1702/11/19–13	N	61 28.0	17.091	15.265	–15.4	–19.4	– 2	61 28.1	17.090	15.202	–15.0	–19.4

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2343217.1	1703/ 5/30–18	F	61 23.3	16.933	15.726	–19.0	21.7	6	61 23.9	16.938	15.884	–19.8	21.8
2343246.7	1703/ 6/29– 1	F	61 12.7	16.886	16.476	–23.0	23.3	–15	61 16.8	16.881	16.327	–22.2	23.3
2343409.1	1703/12/ 8–16	N	61 12.5	17.073	16.003	–21.3	–22.7	17	61 17.5	17.060	16.428	–23.0	–22.8
2343438.6	1704/ 1/ 7– 2	N	61 26.6	17.134	16.725	–23.9	–22.5	– 5	61 27.1	17.134	16.744	–23.9	–22.5
2343630.6	1704/ 7/17– 2	F	61 23.5	16.927	16.634	–24.0	21.3	5	61 24.1	16.922	16.529	–23.6	21.2
2343660.1	1704/ 8/15– 9	F	61 14.1	16.875	15.308	–18.3	14.0	–16	61 18.2	16.885	15.840	–20.9	14.2
2343822.5	1705/ 1/25– 5	N	61 17.6	17.072	16.217	–23.0	–19.0	14	61 21.3	17.051	15.776	–20.9	–18.8
2343852.0	1705/ 2/23–15	N	61 25.7	17.040	14.673	–14.4	– 9.7	– 7	61 26.6	17.035	14.917	–16.0	– 9.8
2344044.0	1705/ 9/ 3– 9	F	61 26.1	16.946	14.322	–12.1	7.6	6	61 26.6	16.944	14.178	–10.7	7.5
2344073.5	1705/10/ 2–17	F	61 14.8	16.987	13.579	0.3	– 3.7	–16	61 19.3	16.974	13.684	– 4.2	– 3.4
2344235.9	1706/ 3/14–17	N	61 17.6	17.012	13.694	– 6.2	– 2.5	12	61 20.5	17.020	13.586	– 2.6	– 2.3
2344265.5	1706/ 4/13– 1	N	61 20.7	17.011	13.753	7.0	8.8	– 8	61 22.1	16.999	13.636	4.4	8.7
2344457.4	1706/10/21–19	F	61 27.1	17.081	13.955	10.1	–10.7	4	61 27.5	17.081	14.072	11.3	–10.8
2344486.9	1706/11/20– 5	F	61 12.6	17.064	15.526	21.5	–19.6	–17	61 18.0	17.056	14.847	17.7	–19.4
2344649.4	1707/ 5/ 2– 3	N	61 15.9	16.974	14.580	16.4	15.1	12	61 18.4	16.979	15.075	19.3	15.3
2344678.9	1707/ 5/31–10	N	61 18.5	16.925	16.456	25.3	21.8	– 9	61 20.1	16.924	16.099	23.9	21.8
2344870.8	1707/12/ 9– 7	F	61 31.0	17.111	17.047	27.1	–22.8	3	61 31.1	17.110	17.106	27.3	–22.8
2344900.4	1708/ 1/ 7–18	F	61 10.9	17.023	16.915	27.3	–22.4	–20	61 17.5	16.995	17.271	28.3	–22.5
2345062.8	1708/ 6/18–10	N	61 16.7	16.882	17.274	28.3	23.4	12	61 19.1	16.880	17.291	28.3	23.4
2345092.3	1708/ 7/17–17	N	61 19.1	16.906	16.503	25.7	21.1	–10	61 20.6	16.903	16.837	26.8	21.2
2345254.7	1708/12/27–10	F	61 6.2	17.007	17.120	28.1	–23.3	22	61 14.3	16.980	16.675	26.4	–23.3
2345284.3	1709/ 1/25–20	F	61 30.5	17.121	15.749	22.3	–18.8	0	61 30.5	17.121	15.762	22.4	–18.8
2345313.8	1709/ 2/24– 7	F	61 3.9	16.981	13.737	10.6	– 9.5	–23	61 12.3	16.953	14.533	16.8	– 9.8
2345476.2	1709/ 8/ 5–17	N	61 15.8	16.933	15.035	19.3	16.9	12	61 18.2	16.930	14.570	16.4	16.8
2345505.8	1709/ 9/ 4– 1	N	61 18.5	16.996	13.621	7.3	7.4	–10	61 20.1	17.003	13.838	10.1	7.5
2345668.2	1710/ 2/13–23	F	61 8.4	17.049	14.163	13.8	–13.2	19	61 15.1	17.035	13.687	8.3	–12.9
2345697.7	1710/ 3/15– 9	F	61 27.8	17.067	13.505	0.3	– 2.2	– 3	61 27.8	17.068	13.509	1.0	– 2.3
2345889.7	1710/ 9/23– 2	N	61 19.4	17.001	13.527	– 2.7	0.2	11	61 21.5	16.982	13.656	– 6.0	0.0
2345919.2	1710/10/22–11	N	61 21.2	17.022	14.553	–15.4	–11.0	–11	61 23.1	17.026	14.231	–12.7	–10.8
2346081.6	1711/ 4/ 3–10	F	61 11.1	16.943	13.878	– 9.2	5.1	18	61 16.9	16.930	14.405	–14.0	5.4
2346111.1	1711/ 5/ 2–18	F	61 26.9	16.940	15.493	–20.1	15.3	– 3	61 27.1	16.938	15.365	–19.4	15.3
2346303.1	1711/11/10–12	N	61 23.9	17.044	15.866	–21.6	–17.1	10	61 25.4	17.040	16.206	–23.0	–17.2
2346332.6	1711/12/ 9–23	N	61 20.1	17.100	16.952	–26.0	–22.8	–13	61 22.9	17.083	16.846	–25.5	–22.8
2346495.0	1712/ 5/20–18	F	61 9.5	16.858	16.354	–23.7	20.1	18	61 15.0	16.872	16.732	–25.0	20.2
2346524.6	1712/ 6/19– 1	F	61 24.0	16.939	16.810	–25.0	23.4	– 3	61 24.2	16.937	16.847	–25.1	23.4
2346716.5	1712/12/28– 1	N	61 25.3	17.137	16.476	–23.2	–23.3	7	61 26.1	17.134	16.319	–22.5	–23.3
2346746.0	1713/ 1/26–12	N	61 16.0	17.068	14.998	–16.0	–18.6	–15	61 19.9	17.061	15.504	–18.9	–18.8
2346908.5	1713/ 7/ 8– 2	F	61 9.3	16.864	15.895	–20.9	22.5	18	61 14.8	16.850	15.423	–18.2	22.4
2346938.0	1713/ 8/ 6– 9	F	61 25.1	16.931	14.776	–13.1	16.7	– 4	61 25.3	16.935	14.866	–13.8	16.8
2347129.9	1714/ 2/14–14	N	61 27.4	17.071	14.442	– 8.5	–13.0	5	61 27.7	17.069	14.371	– 7.5	–12.9
2347159.5	1714/ 3/16– 0	N	61 12.7	16.967	14.072	2.5	– 2.0	–17	61 17.7	16.938	14.092	– 1.6	– 2.3
2347321.9	1714/ 8/25– 9	F	61 12.3	16.864	14.267	– 6.2	10.9	18	61 17.5	16.844	14.155	– 2.2	10.6
2347351.4	1714/ 9/23–17	F	61 27.2	17.001	14.315	4.1	– 0.1	– 4	61 27.5	16.999	14.289	3.3	0.0
2347543.4	1715/ 4/ 4– 1	N	61 24.6	17.025	14.624	8.2	5.4	3	61 24.7	17.029	14.673	8.8	5.4
2347572.9	1715/ 5/ 3–10	N	61 6.8	16.927	15.394	16.2	15.5	–19	61 12.7	16.904	15.031	13.3	15.3

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2347735.3	1715/10/12–18	F	61 14.3	16.988	14.682	9.2	– 7.4	17	61 18.8	16.984	15.010	12.2	– 7.6
2347764.8	1715/11/11– 4	F	61 27.1	17.119	15.690	16.6	–17.3	– 5	61 27.7	17.118	15.589	16.0	–17.2
2347956.8	1716/ 5/21–10	N	61 22.5	16.970	15.906	17.8	20.2	3	61 22.6	16.971	15.941	17.9	20.2
2347986.3	1716/ 6/19–17	N	61 5.7	16.835	16.000	19.1	23.4	–19	61 11.7	16.837	16.048	19.1	23.4
2348148.7	1716/11/29– 7	F	61 20.2	17.073	15.946	17.9	–21.5	14	61 23.6	17.054	16.095	18.6	–21.6
2348178.3	1716/12/28–17	F	61 28.3	17.096	16.087	18.3	–23.2	– 8	61 29.4	17.094	16.147	18.6	–23.3
2348370.2	1717/ 7/ 8–17	N	61 23.3	16.912	15.927	17.5	22.5	3	61 23.4	16.911	15.898	17.3	22.4
2348399.8	1717/ 8/ 7– 0	N	61 6.3	16.869	15.102	12.7	16.6	–19	61 12.3	16.868	15.476	15.2	16.8
2348562.2	1718/ 1/16–19	F	61 23.3	17.084	15.769	16.5	–20.9	12	61 25.7	17.080	15.605	15.3	–20.8
2348591.7	1718/ 2/15– 6	F	61 24.4	17.086	14.999	10.4	–12.8	–10	61 26.1	17.077	15.181	12.0	–12.9
2348783.6	1718/ 8/26– 0	N	61 22.8	16.998	14.903	9.5	10.6	3	61 22.9	16.997	14.867	9.0	10.6
2348813.2	1718/ 9/24– 9	N	61 5.3	16.958	14.373	0.8	– 0.4	–20	61 11.7	16.974	14.512	4.7	0.0
2348975.6	1719/ 3/ 6– 8	F	61 22.9	17.083	14.662	6.6	– 5.8	10	61 24.6	17.078	14.582	4.7	– 5.7
2349005.1	1719/ 4/ 4–17	F	61 20.3	16.977	14.471	– 2.7	5.6	–12	61 22.7	16.977	14.459	– 0.2	5.5
2349167.5	1719/ 9/14– 1	N	60 58.6	16.899	14.380	5.6	3.7	24	61 7.8	16.857	14.308	0.7	3.3
2349197.1	1719/10/13–10	N	61 26.6	17.040	14.499	– 3.9	– 7.6	2	61 26.7	17.038	14.510	– 4.2	– 7.6
2349226.6	1719/11/11–20	N	61 6.3	16.990	14.972	–12.6	–17.4	–21	61 13.5	16.973	14.663	– 9.0	–17.2
2349389.0	1720/ 4/22–18	F	61 23.6	16.948	14.607	– 7.8	12.4	9	61 25.0	16.947	14.749	– 9.5	12.5
2349418.6	1720/ 5/22– 1	F	61 18.9	16.886	15.410	–15.7	20.4	–12	61 21.6	16.871	15.156	–13.7	20.3
2349581.0	1720/10/31–12	N	61 4.8	16.953	14.517	– 9.5	–14.3	22	61 12.6	16.918	15.015	–13.7	–14.6
2349610.5	1720/11/29–22	N	61 28.7	17.100	15.714	–17.6	–21.6	– 1	61 28.7	17.099	15.705	–17.5	–21.6
2349640.0	1720/12/29– 9	N	61 1.7	17.042	16.193	–21.2	–23.2	–24	61 10.5	16.999	16.040	–20.1	–23.3
2349802.5	1721/ 6/10– 2	F	61 21.2	16.913	16.052	–20.2	23.0	8	61 22.4	16.919	16.218	–20.9	23.0
2349832.0	1721/ 7/ 9– 9	F	61 16.3	16.907	16.400	–22.0	22.4	–13	61 19.1	16.905	16.430	–22.0	22.4
2349994.4	1721/12/19– 0	N	61 8.6	17.065	16.251	–22.0	–23.4	20	61 14.9	17.048	16.496	–22.9	–23.4
2350023.9	1722/ 1/17–11	N	61 27.4	17.133	16.428	–22.1	–20.7	– 3	61 27.5	17.134	16.474	–22.3	–20.8
2350215.9	1722/ 7/28– 9	F	61 21.8	16.927	16.199	–21.8	19.1	9	61 23.1	16.918	15.989	–20.8	19.0
2350245.4	1722/ 8/26–16	F	61 18.2	16.910	14.873	–14.6	10.4	–12	61 21.0	16.919	15.266	–17.1	10.6
2350407.8	1723/ 2/ 5–14	N	61 13.7	17.051	15.624	–19.9	–16.0	16	61 18.6	17.028	15.122	–16.9	–15.7
2350437.4	1723/ 3/ 7– 0	N	61 26.6	17.032	14.321	–10.2	– 5.6	– 6	61 27.0	17.029	14.447	–11.4	– 5.7
2350629.3	1723/ 9/14–17	F	61 24.9	16.954	14.042	– 8.0	3.5	8	61 26.0	16.951	13.922	– 5.8	3.3
2350658.8	1723/10/14– 1	F	61 18.9	17.023	13.784	4.5	– 7.9	–13	61 22.1	17.010	13.726	0.8	– 7.7
2350821.3	1724/ 3/25– 1	N	61 13.6	16.979	13.608	– 1.9	1.8	15	61 17.6	16.991	13.651	2.4	2.1
2350850.8	1724/ 4/23– 9	N	61 22.0	17.003	14.138	10.8	12.6	– 6	61 22.7	16.994	13.992	9.0	12.5
2351042.7	1724/11/ 1– 3	F	61 26.4	17.091	14.415	13.8	–14.5	7	61 27.1	17.092	14.641	15.5	–14.6
2351072.3	1724/11/30–14	F	61 16.7	17.089	16.137	23.7	–21.7	–15	61 20.9	17.083	15.572	21.0	–21.6
2351234.7	1725/ 5/12–10	N	61 12.1	16.942	15.117	19.4	18.1	15	61 15.8	16.949	15.749	22.4	18.3
2351264.2	1725/ 6/10–18	N	61 20.4	16.929	16.865	26.5	23.0	– 7	61 21.2	16.930	16.678	25.8	23.0
2351456.2	1725/12/19–16	F	61 30.4	17.115	17.292	27.8	–23.4	4	61 30.7	17.112	17.333	27.9	–23.4
2351485.7	1726/ 1/18– 3	F	61 14.9	17.031	16.458	25.4	–20.6	–18	61 20.3	17.009	17.027	27.3	–20.7
2351648.1	1726/ 6/29–18	N	61 13.3	16.864	17.202	28.1	23.2	14	61 16.9	16.858	16.987	27.3	23.2
2351677.6	1726/ 7/29– 0	N	61 21.4	16.921	15.960	23.4	18.9	– 6	61 22.2	16.921	16.243	24.5	19.0
2351840.1	1727/ 1/ 7–18	F	61 1.1	16.990	16.774	27.2	–22.4	25	61 10.9	16.956	15.988	23.9	–22.2
2351869.6	1727/ 2/ 6– 5	F	61 30.0	17.109	15.095	19.2	–15.8	2	61 30.0	17.110	15.021	18.8	–15.7
2351899.1	1727/ 3/ 7–15	F	61 8.2	16.986	13.462	6.5	– 5.3	–20	61 15.1	16.963	13.975	12.4	– 5.6

Table 16

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1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2352061.5	1727/ 8/17– 1	N	61 12.8	16.927	14.452	16.1	13.7	14	61 16.4	16.921	13.981	12.2	13.5
2352091.1	1727/ 9/15– 8	N	61 21.1	17.022	13.432	3.2	3.2	– 6	61 22.0	17.027	13.514	5.3	3.3
2352253.5	1728/ 2/25– 7	F	61 3.2	17.012	13.681	9.9	– 9.3	22	61 11.6	16.998	13.380	3.4	– 9.0
2352283.0	1728/ 3/25–17	F	61 27.5	17.052	13.525	– 4.0	2.1	0	61 27.5	17.052	13.524	– 4.0	2.1
2352312.6	1728/ 4/24– 1	F	61 4.0	16.850	14.513	–16.7	12.9	–22	61 11.8	16.837	13.851	–10.9	12.6
2352475.0	1728/10/ 3–10	N	61 17.1	17.005	13.621	– 7.0	– 4.1	13	61 20.2	16.982	13.932	–10.8	– 4.3
2352504.5	1728/11/ 1–19	N	61 24.0	17.046	15.123	–19.1	–14.7	– 8	61 25.2	17.049	14.806	–17.2	–14.6
2352666.9	1729/ 4/13–18	F	61 5.9	16.899	14.168	–13.3	9.2	21	61 13.3	16.888	14.964	–18.4	9.5
2352696.5	1729/ 5/13– 2	F	61 27.0	16.928	16.079	–23.1	18.3	– 1	61 27.0	16.927	16.048	–23.0	18.3
2352726.0	1729/ 6/11– 9	F	61 2.7	16.799	16.979	–27.3	23.1	–23	61 10.9	16.770	16.692	–26.0	23.0
2352888.4	1729/11/20–21	N	61 21.9	17.047	16.433	–24.4	–19.9	12	61 24.1	17.041	16.782	–25.7	–20.0
2352917.9	1729/12/20– 8	N	61 22.8	17.111	17.039	–26.6	–23.4	–11	61 24.8	17.098	17.113	–26.8	–23.4
2353080.4	1730/ 6/ 1– 2	F	61 4.4	16.819	16.709	–25.7	22.0	21	61 11.6	16.834	16.892	–26.1	22.1
2353109.9	1730/ 6/30– 9	F	61 24.5	16.939	16.650	–24.8	23.2	– 1	61 24.5	16.939	16.669	–24.9	23.2
2353139.4	1730/ 7/29–16	F	61 0.6	16.830	14.959	–17.9	18.7	–23	61 9.0	16.841	15.837	–22.1	19.0
2353301.8	1731/ 1/ 8–10	N	61 23.4	17.131	16.097	–22.2	–22.3	9	61 24.8	17.127	15.811	–20.9	–22.2
2353331.4	1731/ 2/ 6–21	N	61 18.8	17.069	14.500	–13.0	–15.5	–13	61 21.7	17.065	14.917	–16.0	–15.7
2353493.8	1731/ 7/19– 9	F	61 4.6	16.841	15.438	–19.4	20.9	21	61 11.8	16.822	14.826	–15.3	20.8
2353523.3	1731/ 8/17–16	F	61 26.1	16.949	14.342	–10.0	13.5	0	61 26.1	16.950	14.358	–10.1	13.5
2353552.8	1731/ 9/16– 0	F	61 2.4	16.868	13.764	1.6	2.9	–22	61 10.9	16.872	13.900	– 4.3	3.3
2353715.3	1732/ 2/25–23	N	61 25.5	17.055	14.100	– 4.7	– 9.1	7	61 26.3	17.052	14.051	– 3.0	– 9.0
2353744.8	1732/ 3/26– 8	N	61 15.9	16.966	14.168	6.8	2.3	–15	61 19.6	16.942	14.035	3.2	2.1
2353907.2	1732/ 9/ 4–17	F	61 8.1	16.857	13.994	– 2.3	6.9	20	61 14.8	16.832	14.046	2.6	6.6
2353936.7	1732/10/ 4– 1	F	61 28.5	17.020	14.462	8.4	– 4.4	– 1	61 28.5	17.020	14.440	8.1	– 4.3
2353966.3	1732/11/ 2–11	F	61 0.8	16.991	15.346	17.5	–14.9	–24	61 10.3	16.957	14.811	13.3	–14.6
2354128.7	1733/ 4/14– 9	N	61 22.8	17.002	14.906	12.4	9.4	6	61 23.4	17.010	15.033	13.4	9.5
2354158.2	1733/ 5/13–17	N	61 10.6	16.935	15.858	19.2	18.5	–16	61 15.0	16.917	15.534	17.3	18.3
2354320.6	1733/10/23– 3	F	61 10.7	16.986	14.986	13.3	–11.4	19	61 16.6	16.981	15.451	16.3	–11.6
2354350.2	1733/11/21–13	F	61 28.6	17.135	16.112	19.4	–20.0	– 3	61 28.8	17.135	16.061	19.1	–20.0
2354542.1	1734/ 6/ 1–18	N	61 21.2	16.958	16.175	19.6	22.1	5	61 21.6	16.958	16.209	19.8	22.1
2354571.6	1734/ 7/ 1– 1	N	61 10.1	16.857	15.925	18.9	23.1	–16	61 14.5	16.863	16.123	19.7	23.2
2354734.1	1734/12/10–15	F	61 17.0	17.070	16.123	19.3	–22.9	17	61 21.6	17.045	16.141	19.2	–23.0
2354763.6	1735/ 1/ 9– 2	F	61 29.8	17.100	15.868	17.3	–22.2	– 6	61 30.4	17.099	15.960	17.8	–22.2
2354955.5	1735/ 7/20– 1	N	61 22.4	16.911	15.632	15.9	20.8	5	61 22.9	16.909	15.543	15.3	20.8
2354985.1	1735/ 8/18– 8	N	61 11.1	16.904	14.781	9.5	13.3	–17	61 15.5	16.905	15.081	12.1	13.5
2355147.5	1736/ 1/28– 4	F	61 20.1	17.067	15.375	14.1	–18.4	14	61 23.5	17.061	15.158	12.1	–18.2
2355177.0	1736/ 2/26–14	F	61 26.0	17.079	14.712	6.5	– 8.8	– 8	61 27.1	17.072	14.815	7.9	– 8.9
2355369.0	1736/ 9/ 5– 8	N	61 22.4	17.007	14.648	5.5	6.7	5	61 22.8	17.004	14.609	4.5	6.6
2355398.5	1736/10/ 4–17	N	61 10.2	16.999	14.472	– 3.5	– 4.6	–17	61 15.1	17.010	14.458	– 0.2	– 4.4
2355560.9	1737/ 3/16–16	F	61 19.8	17.054	14.505	2.2	– 1.5	12	61 22.4	17.049	14.502	– 0.1	– 1.3
2355590.5	1737/ 4/15– 1	F	61 22.4	16.973	14.690	– 6.7	9.7	– 9	61 23.9	16.973	14.607	– 4.9	9.6
2355782.4	1737/10/23–19	N	61 26.7	17.054	14.754	– 7.8	–11.6	3	61 26.9	17.049	14.808	– 8.5	–11.7
2355811.9	1737/11/22– 5	N	61 11.1	17.019	15.416	–15.3	–20.2	–19	61 16.8	17.003	15.118	–12.7	–20.0
2355974.3	1738/ 5/ 4– 2	F	61 20.6	16.919	14.944	–11.2	15.8	11	61 22.8	16.917	15.169	–13.0	16.0
2356003.9	1738/ 6/ 2– 9	F	61 21.5	16.889	15.784	–17.4	22.2	–10	61 23.2	16.879	15.615	–16.3	22.1

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2356166.3	1738/11/11–20	N	61 0.2	16.948	14.888	–12.7	–17.6	24	61 9.6	16.906	15.461	–16.4	–17.8
2356195.8	1738/12/11– 7	N	61 28.9	17.104	16.047	–18.9	–23.0	1	61 28.9	17.105	16.072	–19.0	–23.0
2356225.4	1739/ 1/ 9–17	N	61 6.3	17.057	16.096	–20.1	–22.1	–20	61 13.6	17.021	16.190	–20.3	–22.2
2356387.8	1739/ 6/21– 9	F	61 18.4	16.894	16.215	–20.6	23.4	11	61 20.6	16.899	16.318	–21.0	23.4
2356417.3	1739/ 7/20–16	F	61 19.4	16.927	16.158	–20.2	20.7	–10	61 21.1	16.927	16.282	–20.8	20.8
2356579.7	1739/12/30– 9	N	61 4.2	17.052	16.283	–21.8	–23.2	22	61 12.0	17.030	16.287	–21.5	–23.1
2356609.3	1740/ 1/28–20	N	61 27.6	17.129	15.996	–19.5	–18.2	– 1	61 27.6	17.129	16.018	–19.6	–18.2
2356638.8	1740/ 2/27– 6	N	61 0.3	16.952	14.618	–12.0	– 8.6	–23	61 9.3	16.929	15.254	–16.3	– 8.9
2356801.2	1740/ 8/ 7–17	F	61 19.6	16.926	15.702	–18.8	16.2	11	61 21.7	16.913	15.414	–17.1	16.1
2356830.7	1740/ 9/ 6– 0	F	61 21.6	16.944	14.547	–10.5	6.4	–10	61 23.4	16.950	14.789	–12.7	6.6
2356993.2	1741/ 2/15–22	N	61 9.3	17.024	15.062	–16.3	–12.4	19	61 15.5	16.999	14.590	–12.4	–12.1
2357022.7	1741/ 3/17– 8	N	61 26.9	17.021	14.130	– 5.8	– 1.3	– 3	61 27.1	17.019	14.171	– 6.6	– 1.3
2357214.6	1741/ 9/25– 1	F	61 23.2	16.961	13.918	– 3.7	– 0.8	10	61 25.0	16.956	13.877	– 1.0	– 1.0
2357244.2	1741/10/24–10	F	61 22.4	17.054	14.128	8.4	–11.8	–11	61 24.6	17.042	13.972	5.5	–11.7
2357406.6	1742/ 4/ 5– 9	N	61 9.1	16.941	13.682	2.3	6.1	18	61 14.4	16.958	13.915	7.1	6.3
2357436.1	1742/ 5/ 4–17	N	61 22.7	16.993	14.615	14.1	16.0	– 4	61 23.0	16.988	14.498	13.1	16.0
2357628.1	1742/11/12–12	F	61 25.1	17.099	14.956	17.0	–17.7	9	61 26.4	17.098	15.290	18.9	–17.8
2357657.6	1742/12/11–23	F	61 20.2	17.108	16.603	25.0	–23.0	–14	61 23.3	17.104	16.223	23.4	–23.0
2357820.0	1743/ 5/23–18	N	61 7.8	16.908	15.643	21.8	20.6	17	61 12.9	16.915	16.327	24.5	20.7
2357849.5	1743/ 6/22– 1	N	61 21.7	16.933	17.067	26.9	23.4	– 4	61 22.0	16.935	17.013	26.7	23.4
2358041.5	1743/12/31– 1	F	61 29.3	17.114	17.260	27.5	–23.1	6	61 30.0	17.108	17.212	27.3	–23.1
2358071.0	1744/ 1/29–12	F	61 18.4	17.035	15.876	22.8	–18.0	–16	61 22.6	17.019	16.506	25.2	–18.2
2358233.4	1744/ 7/10– 1	N	61 9.2	16.846	16.899	27.1	22.2	17	61 14.3	16.834	16.421	25.3	22.1
2358263.0	1744/ 8/ 8– 8	N	61 23.1	16.936	15.373	20.5	16.1	– 4	61 23.4	16.937	15.544	21.3	16.1
2358454.9	1745/ 2/16–14	F	61 28.8	17.093	14.504	15.5	–12.1	3	61 29.1	17.095	14.369	14.5	–12.1
2358484.4	1745/ 3/17–23	F	61 12.1	16.989	13.351	2.2	– 1.0	–18	61 17.5	16.970	13.601	7.6	– 1.3
2358646.9	1745/ 8/27– 8	N	61 9.4	16.920	13.954	12.4	10.0	17	61 14.3	16.911	13.566	7.5	9.8
2358676.4	1745/ 9/25–17	N	61 23.2	17.045	13.401	– 1.0	– 1.1	– 5	61 23.6	17.048	13.401	0.4	– 1.0
2358868.3	1746/ 4/ 6– 1	F	61 26.6	17.034	13.710	– 8.2	6.3	2	61 26.7	17.033	13.760	– 8.9	6.4
2358897.9	1746/ 5/ 5– 9	F	61 8.6	16.860	15.115	–20.1	16.2	–19	61 14.7	16.851	14.380	–15.4	16.0
2359060.3	1746/10/14–18	N	61 14.3	17.008	13.880	–11.2	– 8.3	16	61 18.5	16.980	14.413	–15.5	– 8.5
2359089.8	1746/11/13– 4	N	61 26.3	17.065	15.775	–22.4	–17.9	– 6	61 26.9	17.067	15.521	–21.2	–17.9
2359252.2	1747/ 4/25– 2	F	61 0.1	16.850	14.591	–17.2	13.0	24	61 9.4	16.842	15.635	–22.3	13.3
2359281.8	1747/ 5/24– 9	F	61 26.4	16.914	16.632	–25.6	20.7	2	61 26.5	16.915	16.692	–25.8	20.7
2359311.3	1747/ 6/22–16	F	61 7.8	16.822	17.067	–27.7	23.4	–19	61 14.1	16.800	17.112	–27.6	23.4
2359473.7	1747/12/ 2– 6	N	61 19.4	17.048	16.904	–26.5	–21.9	13	61 22.5	17.038	17.152	–27.3	–22.0
2359503.3	1747/12/31–16	N	61 25.0	17.117	16.859	–26.2	–23.1	– 8	61 26.2	17.107	17.055	–26.9	–23.1
2359665.7	1748/ 6/11– 9	F	60 58.7	16.779	16.892	–26.9	23.1	24	61 7.9	16.793	16.744	–26.1	23.2
2359695.2	1748/ 7/10–16	F	61 24.3	16.938	16.292	–23.9	22.1	2	61 24.4	16.939	16.223	–23.6	22.1
2359724.7	1748/ 8/ 9– 0	F	61 6.1	16.873	14.477	–15.1	15.9	–20	61 12.6	16.883	15.242	–19.5	16.1
2359887.2	1749/ 1/18–19	N	61 21.0	17.121	15.558	–20.3	–20.4	11	61 23.1	17.115	15.164	–18.1	–20.3
2359916.7	1749/ 2/17– 6	N	61 21.1	17.067	14.059	– 9.4	–11.9	–11	61 23.1	17.065	14.343	–12.2	–12.1
2360079.1	1749/ 7/29–17	F	60 59.3	16.818	14.896	–17.2	18.6	24	61 8.5	16.793	14.239	–11.7	18.4
2360108.6	1749/ 8/28– 0	F	61 26.4	16.965	13.979	– 6.3	9.8	2	61 26.5	16.963	13.953	– 5.9	9.7
2360138.2	1749/ 9/26– 8	F	61 8.0	16.914	13.829	5.8	– 1.3	–19	61 14.7	16.914	13.743	0.5	– 1.0

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2360300.6	1750/ 3/ 8– 8	N	61 23.0	17.034	13.886	– 0.5	– 4.9	8	61 24.5	17.031	13.909	1.8	– 4.7
2360330.1	1750/ 4/ 6–16	N	61 18.6	16.963	14.418	11.1	6.6	–12	61 21.2	16.944	14.179	8.0	6.4
2360492.5	1750/ 9/16– 1	F	61 3.5	16.849	13.847	1.8	2.8	23	61 11.9	16.818	14.130	7.4	2.4
2360522.1	1750/10/15– 9	F	61 29.2	17.037	14.761	12.7	– 8.5	1	61 29.2	17.037	14.785	12.9	– 8.5
2360551.6	1750/11/13–19	F	61 6.2	17.030	15.889	20.7	–18.1	–21	61 13.9	16.997	15.364	17.6	–17.9
2360714.0	1751/ 4/25–17	N	61 20.5	16.977	15.298	16.2	13.2	8	61 21.6	16.988	15.521	17.5	13.3
2360743.5	1751/ 5/25– 1	N	61 13.9	16.942	16.276	21.6	20.8	–14	61 17.0	16.929	16.062	20.5	20.7
2360906.0	1751/11/ 3–11	F	61 6.7	16.983	15.387	17.0	–15.0	21	61 14.0	16.974	15.928	19.6	–15.3
2360935.5	1751/12/ 2–22	F	61 29.4	17.147	16.436	21.4	–22.0	– 2	61 29.5	17.147	16.428	21.3	–22.0
2360965.0	1752/ 1/ 1– 9	F	61 1.5	17.013	15.875	19.9	–23.0	–24	61 10.8	16.993	16.265	21.4	–23.1
2361127.4	1752/ 6/12– 1	N	61 19.3	16.944	16.299	20.8	23.2	8	61 20.4	16.943	16.271	20.6	23.2
2361157.0	1752/ 7/11– 8	N	61 14.0	16.879	15.690	17.8	22.1	–13	61 17.1	16.887	15.967	19.2	22.1
2361319.4	1752/12/21– 0	F	61 13.3	17.062	16.115	19.8	–23.4	19	61 19.1	17.031	15.948	18.7	–23.4
2361348.9	1753/ 1/19–11	F	61 30.8	17.098	15.509	15.4	–20.2	– 4	61 31.0	17.099	15.587	15.9	–20.3
2361540.9	1753/ 7/30– 8	N	61 20.9	16.910	15.248	13.6	18.5	8	61 22.0	16.905	15.104	12.4	18.4
2361570.4	1753/ 8/28–15	N	61 15.2	16.937	14.518	5.8	9.5	–13	61 18.3	16.938	14.704	8.3	9.7
2361732.8	1754/ 2/ 7–13	F	61 16.4	17.044	14.952	11.0	–15.2	16	61 20.8	17.036	14.741	8.2	–15.0
2361762.3	1754/ 3/ 8–23	F	61 27.1	17.068	14.538	2.3	– 4.6	– 6	61 27.6	17.064	14.570	3.4	– 4.7
2361954.3	1754/ 9/16–16	N	61 21.5	17.015	14.510	1.3	2.5	8	61 22.4	17.011	14.511	– 0.2	2.4
2361983.8	1754/10/16– 1	N	61 14.5	17.035	14.702	– 7.6	– 8.8	–14	61 18.1	17.042	14.581	– 5.0	– 8.6
2362146.2	1755/ 3/28– 1	F	61 16.0	17.019	14.486	– 2.1	2.8	14	61 19.7	17.015	14.598	– 4.9	3.0
2362175.8	1755/ 4/26–.9	F	61 24.0	16.968	15.008	–10.5	13.4	– 7	61 24.8	16.968	14.906	– 9.3	13.3
2362367.7	1755/11/ 4– 3	N	61 26.2	17.065	15.099	–11.4	–15.3	6	61 26.8	17.058	15.207	–12.3	–15.3
2362397.3	1755/12/ 3–13	N	61 15.4	17.041	15.788	–17.2	–22.1	–16	61 19.8	17.027	15.577	–15.6	–22.0
2362559.7	1756/ 5/14–10	F	61 17.0	16.888	15.303	–14.0	18.8	13	61 20.3	16.885	15.578	–15.8	18.9
2362589.2	1756/ 6/12–17	F	61 23.6	16.892	16.032	–18.4	23.2	– 8	61 24.5	16.885	15.958	–17.9	23.2
2362781.1	1756/12/21–15	N	61 28.4	17.105	16.205	–19.3	–23.4	4	61 28.6	17.106	16.226	–19.4	–23.4
2362810.7	1757/ 1/20– 2	N	61 10.4	17.067	15.833	–18.1	–20.1	–18	61 16.3	17.036	16.090	–19.2	–20.3
2362973.1	1757/ 7/ 1–17	F	61 15.1	16.874	16.194	–20.1	23.1	14	61 18.4	16.878	16.177	–19.9	23.0
2363002.6	1757/ 7/31– 0	F	61 21.9	16.947	15.808	–17.8	18.3	– 8	61 22.8	16.948	15.943	–18.5	18.4
2363165.0	1758/ 1/ 9–18	N	60 59.3	17.033	16.101	–20.7	–22.0	24	61 8.7	17.006	15.870	–19.1	–21.9
2363194.6	1758/ 2/ 8– 5	N	61 27.2	17.121	15.523	–16.3	–15.0	1	61 27.2	17.121	15.499	–16.1	–15.0
2363224.1	1758/ 3/ 9–15	N	61 4.8	16.957	14.378	– 7.7	– 4.3	–21	61 12.1	16.939	14.810	–12.0	– 4.7
2363386.5	1758/ 8/19– 0	F	61 16.9	16.924	15.218	–15.4	12.9	14	61 20.1	16.906	14.909	–12.9	12.7
2363416.1	1758/ 9/17– 8	F	61 24.4	16.974	14.355	– 6.3	2.3	– 7	61 25.4	16.979	14.470	– 8.0	2.4
2363578.5	1759/ 2/27– 7	N	61 4.2	16.990	14.600	–12.2	– 8.4	21	61 12.0	16.965	14.242	– 7.5	– 8.1
2363608.0	1759/ 3/28–16	N	61 26.7	17.007	14.099	– 1.5	3.0	– 1	61 26.7	17.007	14.101	– 1.7	3.0
2363637.5	1759/ 4/27– 0	N	61 1.3	16.867	14.261	9.4	13.7	–22	61 9.7	16.823	13.999	4.0	13.3
2363800.0	1759/10/ 6– 9	F	61 20.9	16.966	13.950	0.5	– 5.1	13	61 23.6	16.959	14.030	3.8	– 5.3
2363829.5	1759/11/ 4–18	F	61 25.2	17.079	14.578	11.9	–15.5	– 8	61 26.7	17.069	14.389	9.9	–15.4
2363991.9	1760/ 4/15–17	N	61 3.9	16.899	13.893	6.3	10.1	20	61 10.9	16.921	14.338	11.3	10.4
2364021.4	1760/ 5/15– 1	N	61 22.9	16.981	15.128	16.9	18.9	– 1	61 22.9	16.980	15.084	16.6	18.9
2364051.0	1760/ 6/13– 8	N	60 57.1	16.834	16.268	23.6	23.2	–23	61 6.0	16.828	15.678	20.7	23.2
2364213.4	1760/11/22–21	F	61 23.2	17.102	15.510	19.6	–20.4	11	61 25.2	17.101	15.907	21.5	–20.5
2364242.9	1760/12/22– 7	F	61 23.1	17.122	16.849	25.4	–23.4	–11	61 25.3	17.120	16.672	24.6	–23.4

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2364405.3	1761/ 6/ 3– 1	N	61 2.8	16.872	16.082	23.4	22.3	21	61 9.7	16.878	16.691	25.6	22.4
2364434.9	1761/ 7/ 2– 9	N	61 22.5	16.938	17.038	26.4	23.0	– 2	61 22.5	16.939	17.041	26.4	23.0
2364464.4	1761/ 7/31–15	N	60 58.2	16.798	15.870	22.7	18.1	–23	61 6.9	16.817	16.626	25.4	18.4
2364626.8	1762/ 1/10–10	F	61 27.6	17.109	16.962	26.3	–21.9	8	61 28.8	17.099	16.780	25.6	–21.9
2364656.3	1762/ 2/ 8–20	F	61 21.4	17.035	15.276	19.5	–14.8	–13	61 24.6	17.024	15.841	22.1	–14.9
2364818.8	1762/ 7/21– 8	N	61 4.7	16.828	16.415	25.3	20.5	21	61 11.4	16.809	15.715	22.2	20.3
2364848.3	1762/ 8/19–15	N	61 24.2	16.950	14.820	17.1	12.7	– 1	61 24.3	16.950	14.871	17.4	12.7
2364877.8	1762/ 9/17–23	N	60 58.5	16.901	13.418	4.9	2.0	–23	61 7.5	16.899	13.947	11.6	2.4
2365040.2	1763/ 2/27–22	F	61 27.1	17.073	14.040	11.5	– 8.1	6	61 27.8	17.075	13.890	9.8	– 8.1
2365069.8	1763/ 3/29– 8	F	61 15.5	16.989	13.407	– 2.1	3.3	–16	61 19.6	16.974	13.442	2.6	3.1
2365232.2	1763/ 9/ 7–16	N	61 5.4	16.913	13.588	8.5	6.0	20	61 11.8	16.900	13.362	2.6	5.7
2365261.7	1763/10/ 7– 1	N	61 24.7	17.064	13.535	– 5.2	– 5.3	– 2	61 24.8	17.066	13.510	– 4.6	– 5.3
2365453.7	1764/ 4/16– 9	F	61 25.1	17.013	14.050	–12.2	10.3	5	61 25.6	17.012	14.202	–13.5	10.4
2365483.2	1764/ 5/15–17	F	61 12.6	16.869	15.753	–23.0	19.1	–17	61 17.3	16.863	15.060	–19.5	18.9
2365645.6	1764/10/25– 3	N	61 11.0	17.008	14.294	–15.1	–12.2	18	61 16.5	16.975	15.054	–19.6	–12.5
2365675.1	1764/11/23–12	N	61 27.9	17.080	16.421	–25.1	–20.5	– 3	61 28.2	17.081	16.267	–24.5	–20.5
2365867.1	1765/ 6/ 3–17	F	61 25.3	16.899	17.065	–27.3	22.4	4	61 25.7	16.900	17.163	–27.6	22.4
2365896.6	1765/ 7/ 3– 0	F	61 12.3	16.845	16.919	–27.2	23.0	–17	61 17.0	16.829	17.228	–28.1	23.0
2366059.0	1765/12/12–15	N	61 16.3	17.045	17.180	–27.8	–23.1	15	61 20.5	17.031	17.208	–27.8	–23.2
2366088.6	1766/ 1/11– 1	N	61 26.6	17.118	16.440	–24.9	–21.8	– 6	61 27.3	17.111	16.672	–25.8	–21.9
2366280.5	1766/ 7/22– 0	F	61 23.6	16.938	15.785	–22.1	20.3	4	61 24.0	16.938	15.596	–21.2	20.3
2366310.1	1766/ 8/20– 7	F	61 11.0	16.914	14.035	–11.8	12.5	–17	61 15.8	16.922	14.611	–16.1	12.7
2366472.5	1767/ 1/30– 4	N	61 17.9	17.105	14.945	–17.7	–17.7	13	61 21.0	17.098	14.499	–14.6	–17.6
2366502.0	1767/ 2/28–14	N	61 22.9	17.063	13.729	– 5.4	– 7.9	– 9	61 24.2	17.062	13.878	– 7.9	– 8.0
2366694.0	1767/ 9/ 8– 8	F	61 26.2	16.980	13.730	– 2.4	5.8	4	61 26.5	16.975	13.712	– 1.2	5.7
2366723.5	1767/10/ 7–16	F	61 13.0	16.956	14.055	10.1	– 5.6	–17	61 18.2	16.954	13.791	5.5	– 5.3
2366885.9	1768/ 3/18–16	N	61 20.0	17.009	13.821	3.8	– 0.6	11	61 22.3	17.006	13.973	6.8	– 0.4
2366915.4	1768/ 4/17– 0	N	61 20.7	16.958	14.814	15.1	10.6	–10	61 22.5	16.944	14.526	12.8	10.4
2367107.4	1768/10/25–18	F	61 29.2	17.050	15.198	16.7	–12.5	3	61 29.4	17.052	15.299	17.3	–12.5
2367136.9	1768/11/24– 4	F	61 11.0	17.062	16.397	23.3	–20.7	–19	61 17.3	17.032	15.991	21.3	–20.5
2367299.3	1769/ 5/ 6– 1	N	61 17.5	16.948	15.758	19.6	16.5	11	61 19.5	16.963	16.058	21.0	16.7
2367328.9	1769/ 6/ 4– 8	N	61 16.7	16.947	16.578	23.4	22.5	–10	61 18.7	16.939	16.504	23.0	22.4
2367491.3	1769/11/13–20	F	61 2.2	16.978	15.829	20.2	–18.2	23	61 11.1	16.964	16.330	22.2	–18.5
2367520.8	1769/12/13– 6	F	61 29.7	17.154	16.587	22.5	–23.2	1	61 29.7	17.154	16.583	22.5	–23.2
2367550.3	1770/ 1/11–17	F	61 6.3	17.027	15.558	18.6	–21.7	–21	61 14.1	17.013	16.116	21.1	–21.8
2367712.8	1770/ 6/23– 9	N	61 16.8	16.930	16.241	21.1	23.4	10	61 18.7	16.926	16.091	20.3	23.4
2367742.3	1770/ 7/22–16	N	61 17.3	16.900	15.334	16.1	20.2	–11	61 19.2	16.910	15.609	17.7	20.3
2367904.7	1771/ 1/ 1– 9	F	61 9.1	17.049	15.905	19.4	–23.0	21	61 16.3	17.011	15.548	17.0	–22.9
2367934.2	1771/ 1/30–20	F	61 31.1	17.093	15.077	12.8	–17.5	– 2	61 31.2	17.094	15.114	13.1	–17.5
2367963.8	1771/ 3/ 1– 6	F	61 2.2	16.924	14.187	3.3	– 7.6	–24	61 11.5	16.884	14.517	8.4	– 8.0
2368126.2	1771/ 8/10–16	N	61 18.9	16.909	14.838	10.8	15.5	10	61 20.8	16.900	14.672	8.8	15.4
2368155.7	1771/ 9/ 8–23	N	61 18.8	16.967	14.353	1.7	5.5	–11	61 20.8	16.967	14.425	4.0	5.7
2368318.1	1772/ 2/18–21	F	61 12.0	17.015	14.571	7.4	–11.5	19	61 17.8	17.006	14.437	3.8	–11.3
2368347.7	1772/ 3/19– 7	F	61 27.6	17.055	14.498	– 2.1	– 0.3	– 3	61 27.8	17.052	14.488	– 1.3	– 0.4
2368539.6	1772/ 9/27– 0	N	61 20.0	17.021	14.504	– 3.1	– 1.8	10	61 21.6	17.015	14.585	– 5.0	– 1.9

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2368569.1	1772/10/26–10	N	61 18.2	17.065	15.043	–11.5	–12.7	–12	61 20.8	17.069	14.870	– 9.5	–12.5
2368731.6	1773/ 4/ 7– 9	F	61 11.7	16.980	14.600	– 6.3	7.0	17	61 16.7	16.978	14.851	– 9.4	7.3
2368761.1	1773/ 5/ 6–17	F	61 25.0	16.961	15.384	–13.8	16.7	– 5	61 25.4	16.962	15.306	–13.1	16.7
2368953.0	1773/11/14–12	N	61 25.1	17.073	15.480	–14.5	–18.4	8	61 26.2	17.063	15.627	–15.4	–18.5
2368982.6	1773/12/13–22	N	61 19.0	17.058	16.022	–18.2	–23.2	–14	61 22.3	17.046	15.936	–17.6	–23.2
2369145.0	1774/ 5/25–17	F	61 12.8	16.855	15.623	–16.2	21.0	17	61 17.5	16.850	15.883	–17.6	21.2
2369174.5	1774/ 6/24– 0	F	61 25.0	16.894	16.117	–18.6	23.4	– 5	61 25.4	16.891	16.112	–18.5	23.4
2369366.5	1775/ 1/ 2– 0	N	61 27.3	17.102	16.162	–18.8	–22.9	6	61 27.9	17.103	16.140	–18.7	–22.9
2369396.0	1775/ 1/31–11	N	61 14.0	17.072	15.476	–15.4	–17.3	–17	61 18.7	17.047	15.790	–17.2	–17.5
2369558.4	1775/ 7/13– 0	F	61 11.2	16.854	16.001	–18.9	21.9	17	61 15.9	16.856	15.839	–17.9	21.8
2369587.9	1775/ 8/11– 7	F	61 23.7	16.966	15.417	–14.8	15.3	– 4	61 24.1	16.966	15.510	–15.4	15.4
2369779.9	1776/ 2/19–13	N	61 26.2	17.110	15.091	–12.6	–11.3	4	61 26.4	17.109	15.029	–12.0	–11.2
2369809.4	1776/ 3/19–23	N	61 8.8	16.960	14.284	– 3.4	0.0	–19	61 14.7	16.947	14.513	– 7.3	– 0.3
2369971.8	1776/ 8/29– 8	F	61 13.6	16.921	14.807	–11.6	9.1	16	61 18.1	16.898	14.546	– 8.3	8.9
2370001.4	1776/ 9/27–16	F	61 26.6	17.002	14.307	– 2.0	– 2.0	– 5	61 27.1	17.005	14.337	– 3.2	– 1.9
2370163.8	1777/ 3/ 9–15	N	60 58.6	16.949	14.277	– 8.0	– 4.2	24	61 8.2	16.925	14.099	– 2.6	– 3.8
2370193.3	1777/ 4/ 8– 0	N	61 25.9	16.991	14.216	2.6	7.2	2	61 26.0	16.992	14.226	3.0	7.3
2370222.9	1777/ 5/ 7– 8	N	61 5.9	16.877	14.717	12.6	16.9	–20	61 12.5	16.841	14.361	8.4	16.7
2370385.3	1777/10/16–17	F	61 18.1	16.969	14.124	4.6	– 9.2	15	61 21.9	16.960	14.352	8.2	– 9.4
2370414.8	1777/11/15– 3	F	61 27.5	17.099	15.085	14.9	–18.6	– 7	61 28.3	17.091	14.916	13.6	–18.5
2370577.2	1778/ 4/27– 1	N	60 58.1	16.852	14.211	9.9	13.8	23	61 7.0	16.880	14.852	15.0	14.1
2370606.8	1778/ 5/26– 9	N	61 22.5	16.968	15.613	19.0	21.1	1	61 22.5	16.970	15.652	19.2	21.2
2370636.3	1778/ 6/24–16	N	61 2.4	16.861	16.462	23.7	23.4	–21	61 9.3	16.860	16.161	22.2	23.4
2370798.7	1778/12/ 4– 5	F	61 20.8	17.103	15.992	21.5	–22.3	13	61 23.7	17.099	16.374	23.1	–22.3
2370828.2	1779/ 1/ 2–16	F	61 25.5	17.130	16.842	24.8	–22.9	– 9	61 26.9	17.130	16.833	24.7	–22.9
2370990.7	1779/ 6/14– 9	N	60 57.3	16.833	16.367	24.3	23.3	23	61 6.1	16.838	16.762	25.5	23.3
2371020.2	1779/ 7/13–16	N	61 22.6	16.942	16.794	25.1	21.8	1	61 22.6	16.941	16.774	25.0	21.8
2371049.7	1779/ 8/11–23	N	61 3.9	16.838	15.367	19.6	15.1	–20	61 10.7	16.857	16.103	22.8	15.4
2371212.1	1780/ 1/21–19	F	61 25.3	17.098	16.466	24.1	–19.8	10	61 27.2	17.084	16.151	22.8	–19.7
2371241.7	1780/ 2/20– 5	F	61 23.9	17.032	14.748	15.7	–11.0	–12	61 26.1	17.024	15.175	18.2	–11.2
2371404.1	1780/ 7/31–16	N	60 59.6	16.809	15.827	22.8	18.0	23	61 8.2	16.781	15.003	18.4	17.8
2371433.6	1780/ 8/29–23	N	61 24.8	16.962	14.363	13.3	8.9	1	61 24.8	16.962	14.326	13.0	8.9
2371463.1	1780/ 9/28– 7	N	61 4.2	16.948	13.428	0.7	– 2.3	–20	61 11.4	16.942	13.660	6.6	– 1.9
2371625.6	1781/ 3/10– 7	F	61 24.8	17.048	13.737	7.3	– 3.9	8	61 26.0	17.051	13.627	4.9	– 3.8
2371655.1	1781/ 4/ 8–16	F	61 18.4	16.988	13.625	– 6.2	7.5	–14	61 21.3	16.975	13.503	– 2.3	7.3
2371817.5	1781/ 9/18– 0	N	61 0.9	16.904	13.375	4.3	1.8	22	61 9.1	16.886	13.379	– 2.4	1.5
2371847.0	1781/10/17– 9	N	61 25.6	17.081	13.830	– 9.3	– 9.4	0	61 25.6	17.080	13.835	– 9.4	– 9.4
2371876.6	1781/11/15–19	N	61 1.9	17.012	15.310	–21.2	–18.7	–22	61 10.2	17.005	14.468	–16.1	–18.5
2372039.0	1782/ 4/27–17	F	61 23.1	16.989	14.514	–15.9	14.0	7	61 24.0	16.988	14.806	–17.7	14.1
2372068.5	1782/ 5/27– 0	F	61 16.2	16.878	16.349	–25.2	21.3	–14	61 19.5	16.875	15.796	–22.8	21.2
2372230.9	1782/11/ 5–11	N	61 7.2	17.006	14.829	–18.7	–15.8	20	61 14.1	16.966	15.767	–23.1	–16.1
2372260.5	1782/12/ 4–21	N	61 29.0	17.090	16.956	–26.9	–22.4	– 2	61 29.1	17.091	16.901	–26.8	–22.3
2372452.4	1783/ 6/15– 0	F	61 23.6	16.885	17.304	–28.2	23.3	8	61 24.5	16.885	17.350	–28.4	23.3
2372481.9	1783/ 7/14– 7	F	61 16.3	16.867	16.561	–26.0	21.7	–14	61 19.6	16.857	17.014	–27.5	21.8
2372644.4	1783/12/23–23	N	61 12.7	17.038	17.191	–28.1	–23.4	18	61 18.1	17.020	16.916	–27.0	–23.4

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2372673.9	1784/ 1/22–10	N	61 27.6	17.115	15.858	−22.8	−19.7	− 4	61 27.9	17.111	16.049	−23.6	−19.7
2372865.8	1784/ 8/ 1– 7	F	61 22.3	16.937	15.201	−19.7	17.9	8	61 23.2	16.937	14.905	−18.0	17.8
2372895.4	1784/ 8/30–15	F	61 15.3	16.952	13.685	− 8.0	8.7	−14	61 18.7	16.958	14.052	−12.0	8.9
2373057.8	1785/ 2/ 9–13	N	61 14.3	17.083	14.346	−14.4	−14.4	15	61 18.5	17.075	13.927	−10.3	−14.2
2373087.3	1785/ 3/10–23	N	61 24.1	17.057	13.543	− 1.2	− 3.6	− 7	61 24.8	17.056	13.584	− 3.2	− 3.8
2373279.3	1785/ 9/18–16	F	61 25.4	16.993	13.622	1.7	1.6	7	61 26.2	16.985	13.669	3.7	1.4
2373308.8	1785/10/18– 1	F	61 17.4	16.993	14.443	14.2	− 9.7	−15	61 21.3	16.989	14.059	10.4	− 9.5
2373471.2	1786/ 3/30– 0	N	61 16.3	16.979	13.916	8.1	3.7	14	61 19.6	16.977	14.249	11.6	4.0
2373500.8	1786/ 4/28– 8	N	61 22.4	16.952	15.327	18.9	14.2	− 7	61 23.4	16.942	15.056	17.3	14.1
2373692.7	1786/11/ 6– 2	F	61 28.8	17.061	15.735	20.3	−16.0	6	61 29.2	17.062	15.919	21.1	−16.1
2373722.2	1786/12/ 5–13	F	61 15.3	17.087	16.775	25.1	−22.4	−17	61 20.2	17.061	16.571	24.2	−22.3
2373884.6	1787/ 5/17– 9	N	61 14.0	16.918	16.222	22.5	19.3	13	61 17.1	16.935	16.531	23.7	19.4
2373914.2	1787/ 6/15–16	N	61 18.9	16.952	16.702	24.3	23.3	− 8	61 20.0	16.947	16.747	24.4	23.3
2374106.1	1787/12/24–15	F	61 29.4	17.157	16.514	22.8	−23.4	3	61 29.6	17.156	16.464	22.6	−23.4
2374135.7	1788/ 1/23– 2	F	61 10.7	17.036	15.122	16.4	−19.5	−19	61 17.0	17.028	15.731	19.7	−19.7
2374298.1	1788/ 7/ 3–16	N	61 13.7	16.915	15.999	20.6	22.9	14	61 16.7	16.907	15.693	19.0	22.8
2374327.6	1788/ 8/ 1–23	N	61 20.0	16.921	14.911	13.7	17.7	− 8	61 21.1	16.930	15.124	15.2	17.8
2374490.0	1789/ 1/11–18	F	61 4.4	17.030	15.519	18.0	−21.6	23	61 13.1	16.985	15.021	14.4	−21.5
2374519.6	1789/ 2/10– 4	F	61 30.9	17.083	14.648	9.5	−14.2	1	61 30.9	17.083	14.642	9.5	−14.2
2374549.1	1789/ 3/11–14	F	61 6.8	16.929	14.095	− 0.9	− 3.4	−22	61 14.5	16.896	14.216	4.0	− 3.7
2374711.5	1789/ 8/20–23	N	61 16.3	16.908	14.459	7.4	12.1	13	61 19.2	16.894	14.329	4.6	11.9
2374741.0	1789/ 9/19– 7	N	61 21.7	16.994	14.313	− 2.5	1.3	− 8	61 22.9	16.994	14.296	− 0.7	1.4
2374903.5	1790/ 3/ 1– 6	F	61 7.1	16.980	14.283	3.4	− 7.5	21	61 14.4	16.972	14.295	− 1.0	− 7.1
2374933.0	1790/ 3/30–15	F	61 27.5	17.038	14.599	− 6.4	4.0	− 1	61 27.5	17.037	14.584	− 6.1	4.0
2374962.5	1790/ 4/29– 0	F	61 0.5	16.864	15.169	−14.5	14.4	−24	61 9.4	16.841	14.784	−10.7	14.1
2375124.9	1790/10/ 8– 8	N	61 17.9	17.024	14.635	− 7.3	− 6.0	13	61 20.5	17.017	14.829	− 9.6	− 6.2
2375154.5	1790/11/ 6–18	N	61 21.4	17.089	15.460	−15.0	−16.2	− 9	61 23.0	17.092	15.289	−13.7	−16.1
2375316.9	1791/ 4/18–17	F	61 6.7	16.935	14.829	−10.4	11.0	19	61 13.4	16.937	15.219	−13.4	11.2
2375346.4	1791/ 5/18– 1	F	61 25.5	16.953	15.761	−16.5	19.5	− 2	61 25.5	16.954	15.729	−16.3	19.5
2375375.9	1791/ 6/16– 8	F	60 59.4	16.765	15.915	−18.7	23.3	−24	61 8.5	16.759	15.872	−18.1	23.3
2375538.4	1791/11/25–20	N	61 23.5	17.078	15.829	−16.9	−20.9	11	61 25.2	17.064	15.968	−17.6	−21.0
2375567.9	1791/12/25– 7	N	61 22.0	17.069	16.072	−18.4	−23.4	−12	61 24.5	17.060	16.109	−18.5	−23.4
2375730.3	1792/ 6/ 5– 1	F	61 8.0	16.821	15.846	−17.8	22.6	19	61 14.3	16.813	16.004	−18.4	22.7
2375759.8	1792/ 7/ 4– 7	F	61 25.9	16.896	16.032	−18.0	22.8	− 1	61 25.9	16.896	16.047	−18.1	22.8
2375789.4	1792/ 8/ 2–14	F	60 59.4	16.807	15.210	−14.0	17.5	−23	61 8.7	16.798	15.662	−16.6	17.8
2375951.8	1793/ 1/12– 9	N	61 25.7	17.095	15.936	−17.5	−21.5	8	61 26.7	17.096	15.845	−16.9	−21.5
2375981.3	1793/ 2/10–20	N	61 17.1	17.073	15.104	−12.1	−14.0	−15	61 20.6	17.053	15.387	−14.1	−14.2
2376143.7	1793/ 7/23– 7	F	61 6.8	16.834	15.674	−17.0	20.0	20	61 13.1	16.832	15.395	−14.9	19.8
2376173.3	1793/ 8/21–15	F	61 25.0	16.983	15.052	−11.2	11.9	− 2	61 25.1	16.983	15.087	−11.6	11.9
2376202.8	1793/ 9/19–23	F	60 58.1	16.896	14.311	− 2.7	1.0	−24	61 7.7	16.907	14.593	− 7.5	1.4
2376365.2	1794/ 3/ 1–22	N	61 24.6	17.094	14.757	− 8.5	− 7.2	5	61 25.2	17.093	14.687	− 7.4	− 7.1
2376394.7	1794/ 3/31– 7	N	61 12.3	16.962	14.333	0.9	4.3	−16	61 16.9	16.952	14.392	− 2.5	4.0
2376557.2	1794/ 9/ 9–16	F	61 9.8	16.915	14.508	− 7.5	5.1	19	61 15.7	16.888	14.359	− 3.5	4.8
2376586.7	1794/10/ 9– 0	F	61 28.2	17.026	14.401	2.2	− 6.3	− 2	61 28.4	17.027	14.393	1.6	− 6.2
2376778.6	1795/ 4/19– 8	N	61 24.5	16.972	14.457	6.5	11.2	4	61 24.9	16.975	14.515	7.4	11.3

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2376808.2	1795/ 5/18–16	N	61 10.1	16.885	15.188	15.2	19.6	–17	61 15.1	16.858	14.832	12.1	19.5
2376970.6	1795/10/28– 2	F	61 14.9	16.970	14.418	8.4	–13.1	17	61 19.8	16.958	14.791	12.1	–13.3
2377000.1	1795/11/26–12	F	61 29.2	17.113	15.576	17.3	–21.0	– 5	61 29.6	17.109	15.463	16.6	–21.0
2377192.1	1796/ 6/ 5–16	N	61 21.5	16.955	16.002	20.4	22.7	4	61 21.7	16.959	16.097	20.9	22.7
2377221.6	1796/ 7/ 4–23	N	61 7.1	16.887	16.451	23.0	22.8	–18	61 12.3	16.890	16.410	22.6	22.8
2377384.0	1796/12/14–14	F	61 17.9	17.099	16.320	22.5	–23.3	15	61 21.8	17.092	16.593	23.5	–23.3
2377413.6	1797/ 1/13– 1	F	61 27.3	17.133	16.603	23.3	–21.4	– 7	61 28.1	17.134	16.691	23.6	–21.5
2377605.5	1797/ 7/23–23	N	61 22.1	16.947	16.389	23.0	19.8	4	61 22.4	16.942	16.291	22.6	19.8
2377635.0	1797/ 8/22– 7	N	61 9.0	16.877	14.906	16.0	11.6	–18	61 14.1	16.894	15.508	19.3	11.9
2377797.5	1798/ 2/ 1– 4	F	61 22.5	17.081	15.872	21.3	–17.0	12	61 25.2	17.064	15.467	19.1	–16.9
2377827.0	1798/ 3/ 2–13	F	61 25.9	17.026	14.350	11.5	– 7.0	– 9	61 27.3	17.021	14.620	13.8	– 7.1
2378018.9	1798/ 9/10– 7	N	61 24.7	16.973	14.043	9.2	4.8	4	61 24.9	16.971	13.968	8.2	4.8
2378048.5	1798/10/ 9–16	N	61 9.3	16.989	13.595	– 3.5	– 6.5	–18	61 14.9	16.981	13.594	1.6	– 6.2
2378210.9	1799/ 3/21–15	F	61 21.8	17.018	13.607	3.0	0.4	11	61 23.9	17.023	13.589	– 0.1	0.6
2378240.4	1799/ 4/20– 0	F	61 20.8	16.984	13.985	–10.1	11.4	–11	61 22.7	16.974	13.773	– 7.1	11.3
2378432.4	1799/10/28–17	N	61 25.9	17.093	14.267	–13.2	–13.3	3	61 26.0	17.092	14.346	–13.8	–13.3
2378461.9	1799/11/27– 4	N	61 6.9	17.043	15.957	–23.6	–21.1	–20	61 13.6	17.035	15.195	–19.8	–21.0
2378624.3	1800/ 5/ 9– 1	F	61 20.4	16.962	15.057	–19.0	17.2	10	61 22.2	16.961	15.490	–21.2	17.3
2378653.8	1800/ 6/ 7– 8	F	61 19.2	16.886	16.818	–26.6	22.7	–11	61 21.4	16.886	16.463	–25.3	22.7
2378816.3	1800/11/16–20	N	61 3.0	17.001	15.423	–21.8	–18.8	22	61 11.4	16.954	16.423	–25.6	–19.1
2378845.8	1800/12/16– 6	N	61 29.5	17.097	17.282	–27.9	–23.3	0	61 29.5	17.097	17.285	–27.9	–23.3
2378875.3	1801/ 1/14–17	N	61 4.5	17.005	16.505	–26.1	–21.3	–23	61 12.7	16.962	17.137	–28.0	–21.4
2379037.7	1801/ 6/26– 8	F	61 21.2	16.870	17.306	–28.3	23.4	10	61 22.9	16.867	17.204	–27.9	23.4
2379067.3	1801/ 7/25–15	F	61 19.7	16.889	16.055	–24.0	19.7	–12	61 21.9	16.882	16.520	–25.7	19.8
2379229.7	1802/ 1/ 4– 8	N	61 8.5	17.026	16.923	–27.4	–22.8	20	61 15.2	17.004	16.332	–25.1	–22.7
2379259.2	1802/ 2/ 2–19	N	61 28.0	17.109	15.214	–19.9	–16.8	– 3	61 28.1	17.107	15.317	–20.4	–16.9
2379451.2	1802/ 8/13–15	F	61 20.3	16.936	14.616	–16.7	14.8	10	61 22.0	16.934	14.264	–14.1	14.7
2379480.7	1802/ 9/11–23	F	61 19.0	16.987	13.463	– 4.0	4.6	–12	61 21.3	16.992	13.642	– 7.4	4.8
2379643.1	1803/ 2/21–21	N	61 10.1	17.055	13.837	–10.7	–10.6	18	61 15.5	17.048	13.527	– 5.6	–10.4
2379672.6	1803/ 3/23– 7	N	61 24.8	17.048	13.520	3.1	0.7	– 4	61 25.1	17.048	13.496	1.8	0.6
2379864.6	1803/10/ 1– 0	F	61 24.1	17.003	13.673	6.0	– 2.7	9	61 25.5	16.992	13.841	8.6	– 2.9
2379894.1	1803/10/30– 9	F	61 21.2	17.025	14.978	18.1	–13.5	–12	61 24.0	17.021	14.543	15.2	–13.4
2380056.5	1804/ 4/10– 8	N	61 12.1	16.944	14.168	12.3	7.9	16	61 16.7	16.944	14.723	16.3	8.2
2380086.1	1804/ 5/ 9–16	N	61 23.5	16.944	15.906	22.1	17.4	– 5	61 23.9	16.938	15.709	21.2	17.3
2380278.0	1804/11/17–11	F	61 27.7	17.068	16.304	23.3	–19.0	7	61 28.6	17.069	16.537	24.2	–19.1
2380307.6	1804/12/16–21	F	61 19.0	17.105	16.940	26.0	–23.3	–14	61 22.7	17.084	16.967	26.0	–23.3
2380470.0	1805/ 5/28–16	N	61 9.9	16.885	16.612	24.7	21.4	16	61 14.3	16.905	16.819	25.4	21.6
2380499.5	1805/ 6/26–23	N	61 20.5	16.956	16.616	24.4	23.4	– 5	61 21.0	16.954	16.719	24.8	23.4
2380691.5	1806/ 1/ 5– 0	F	61 28.6	17.155	16.216	22.1	–22.7	5	61 29.0	17.153	16.080	21.4	–22.7
2380721.0	1806/ 2/ 3–11	F	61 14.5	17.041	14.643	13.6	–16.6	–17	61 19.5	17.037	15.195	17.2	–16.8
2380883.4	1806/ 7/16– ·0	N	61 10.0	16.900	15.600	19.4	21.5	16	61 14.4	16.886	15.150	16.6	21.4
2380912.9	1806/ 8/14– 7	N	61 22.1	16.942	14.485	10.7	14.6	– 5	61 22.6	16.949	14.609	11.9	14.6
2381104.9	1807/ 2/22–13	F	61 30.1	17.070	14.286	5.8	–10.4	2	61 30.2	17.069	14.259	5.2	–10.4
2381134.4	1807/ 3/23–22	F	61 11.0	16.932	14.146	– 5.3	0.9	–19	61 17.1	16.904	14.071	– 0.7	0.6
2381296.8	1807/ 9/ 2– 7	N	61 13.1	16.905	14.161	3.6	8.2	16	61 17.3	16.886	14.133	0.0	8.0

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2381326.4	1807/10/ 1–15	N	61 24.1	17.016	14.414	– 6.8	– 3.0	– 6	61 24.7	17.016	14.350	– 5.5	– 2.9
2381488.8	1808/ 3/12–14	F	61 1.6	16.938	14.120	– 0.8	– 3.2	24	61 10.6	16.933	14.340	– 5.9	– 2.8
2381518.3	1808/ 4/10–23	F	61 26.9	17.018	14.837	–10.6	8.2	2	61 26.9	17.019	14.856	–10.8	8.2
2381547.8	1808/ 5/10– 8	F	61 5.3	16.878	15.625	–17.7	17.6	–21	61 12.4	16.860	15.233	–14.9	17.4
2381710.3	1808/10/19–17	N	61 15.4	17.027	14.897	–11.5	–10.1	14	61 19.0	17.018	15.213	–13.9	–10.3
2381739.8	1808/11/18– 3	N	61 23.9	17.109	15.891	–18.0	–19.2	– 8	61 24.9	17.111	15.766	–17.2	–19.1
2381902.2	1809/ 4/30– 0	F	61 1.2	16.887	15.144	–14.0	14.6	23	61 9.7	16.892	15.626	–16.8	14.9
2381931.7	1809/ 5/29– 8	F	61 25.3	16.944	16.072	–18.6	21.6	1	61 25.3	16.944	16.078	–18.6	21.6
2381961.3	1809/ 6/27–15	F	61 4.8	16.792	15.914	–18.7	23.3	–21	61 12.0	16.791	16.071	–19.2	23.4
2382123.7	1809/12/ 7– 5	N	61 21.3	17.080	16.069	–18.6	–22.6	12	61 23.9	17.061	16.138	–18.8	–22.6
2382153.2	1810/ 1/ 5–16	N	61 24.5	17.076	15.932	–17.7	–22.6	–10	61 26.2	17.069	16.052	–18.3	–22.7
2382315.6	1810/ 6/17– 8	F	61 2.7	16.786	15.924	–18.5	23.4	23	61 10.8	16.775	15.906	–18.1	23.4
2382345.2	1810/ 7/16–15	F	61 26.1	16.899	15.794	–16.6	21.4	1	61 26.1	16.899	15.783	–16.5	21.4
2382374.7	1810/ 8/14–22	F	61 5.2	16.851	14.890	–10.9	14.4	–21	61 12.4	16.843	15.303	–14.0	14.6
2382537.1	1811/ 1/24–18	N	61 23.5	17.084	15.579	–15.3	–19.3	10	61 25.1	17.085	15.426	–14.1	–19.2
2382566.6	1811/ 2/23– 4	N	61 19.6	17.071	14.788	– 8.3	–10.1	–12	61 22.2	17.055	14.986	–10.4	–10.3
2382729.1	1811/ 8/ 4–15	F	61 1.8	16.813	15.273	–14.4	17.4	22	61 10.0	16.808	14.947	–11.2	17.2
2382758.6	1811/ 9/ 2–23	F	61 25.6	16.999	14.764	– 7.3	8.0	0	61 25.7	16.999	14.757	– 7.2	8.0
2382788.1	1811/10/ 2– 7	F	61 3.9	16.946	14.366	1.6	– 3.2	–21	61 11.7	16.953	14.446	– 2.7	– 2.9
2382950.5	1812/ 3/13– 6	N	61 22.5	17.074	14.552	– 4.2	– 2.9	8	61 23.6	17.074	14.514	– 2.7	– 2.8
2382980.1	1812/ 4/11–15	N	61 15.4	16.962	14.516	5.1	8.4	–14	61 18.7	16.955	14.451	2.3	8.2
2383142.5	1812/ 9/21– 0	F	61 5.5	16.908	14.341	– 3.2	0.9	21	61 13.1	16.876	14.354	1.3	0.5
2383172.0	1812/10/20– 9	F	61 29.3	17.046	14.625	6.3	–10.3	– 1	61 29.3	17.046	14.620	6.2	–10.3
2383201.6	1812/11/18–18	F	61 4.1	16.985	15.190	14.5	–19.3	–22	61 12.8	16.955	14.822	10.8	–19.1
2383364.0	1813/ 4/30–16	N	61 22.6	16.951	14.789	10.1	14.8	7	61 23.4	16.954	14.917	11.3	14.9
2383393.5	1813/ 5/29–23	N	61 13.7	16.893	15.610	17.1	21.7	–14	61 17.3	16.873	15.329	15.2	21.6
2383555.9	1813/11/ 8–10	F	61 11.1	16.970	14.790	11.8	–16.5	20	61 17.4	16.953	15.268	15.2	–16.8
2383585.4	1813/12/ 7–20	F	61 30.3	17.123	15.976	18.9	–22.6	– 2	61 30.4	17.121	15.927	18.6	–22.6
2383777.4	1814/ 6/18– 0	N	61 19.8	16.941	16.238	21.0	23.4	6	61 20.6	16.946	16.333	21.5	23.4
2383806.9	1814/ 7/17– 7	N	61 11.3	16.912	16.259	21.5	21.3	–15	61 15.0	16.917	16.393	21.9	21.4
2383969.3	1814/12/26–23	F	61 14.5	17.091	16.436	22.6	–23.4	17	61 19.5	17.079	16.524	22.7	–23.3
2383998.9	1815/ 1/25–10	F	61 28.5	17.132	16.198	21.0	–19.1	– 5	61 28.9	17.134	16.307	21.5	–19.2
2384190.8	1815/ 8/ 5– 7	N	61 21.0	16.951	15.896	20.3	17.2	7	61 21.8	16.942	15.710	19.3	17.1
2384220.4	1815/ 9/ 3–14	N	61 13.5	16.913	14.542	12.1	7.8	–14	61 17.2	16.928	14.963	15.2	8.0
2384382.8	1816/ 2/13–12	F	61 19.0	17.059	15.281	17.8	–13.6	15	61 22.8	17.038	14.858	14.9	–13.4
2384412.3	1816/ 3/13–22	F	61 27.3	17.017	14.110	7.2	– 2.7	– 7	61 28.1	17.014	14.245	9.1	– 2.8
2384604.3	1816/ 9/21–15	N	61 24.1	16.983	13.876	5.0	0.6	6	61 24.7	16.979	13.822	3.3	0.5
2384633.8	1816/10/21– 0	N	61 13.8	17.025	13.909	– 7.5	–10.6	–16	61 18.0	17.015	13.746	– 3.3	–10.3
2384796.2	1817/ 4/ 1–23	F	61 18.3	16.985	13.642	– 1.3	4.7	13	61 21.4	16.991	13.764	– 4.9	4.9
2384825.7	1817/ 5/ 1– 8	F	61 22.6	16.978	14.454	–13.6	15.0	– 9	61 23.8	16.970	14.222	–11.4	14.9
2385017.7	1817/11/ 9– 2	N	61 25.7	17.104	14.807	–16.6	–16.7	5	61 26.0	17.102	14.982	–17.7	–16.8
2385047.2	1817/12/ 8–12	N	61 11.4	17.066	16.488	–25.2	–22.7	–17	61 16.7	17.059	15.914	–22.7	–22.6
2385209.6	1818/ 5/20– 8	F	61 17.1	16.933	15.612	–21.6	19.9	13	61 19.9	16.931	16.142	–23.9	20.0
2385239.2	1818/ 6/18–15	F	61 21.7	16.894	17.093	–27.2	23.4	– 8	61 22.9	16.896	16.935	–26.7	23.4
2385431.1	1818/12/27–15	N	61 29.3	17.100	17.336	–27.9	–23.3	2	61 29.4	17.099	17.330	–27.9	–23.3

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2385460.6	1819/ 1/26– 1	N	61 8.9	17.013	15.951	–23.7	–18.9	–20	61 15.6	16.978	16.734	–26.4	–19.1
2385623.1	1819/ 7/ 7–15	F	61 18.3	16.856	17.068	–27.6	22.6	13	61 21.0	16.849	16.755	–26.4	22.6
2385652.6	1819/ 8/ 5–22	F	61 22.5	16.910	15.480	–21.3	17.0	– 8	61 23.8	16.906	15.857	–22.9	17.1
2385815.0	1820/ 1/15–17	N	61 3.8	17.009	16.421	–25.8	–21.2	22	61 12.0	16.982	15.581	–22.2	–21.0
2385844.5	1820/ 2/14– 4	N	61 27.8	17.099	14.605	–16.4	–13.4	– 1	61 27.8	17.099	14.616	–16.5	–13.4
2385874.1	1820/ 3/14–14	N	61 1.5	16.969	13.282	– 3.1	– 2.4	–23	61 9.9	16.935	13.693	– 9.8	– 2.8
2386036.5	1820/ 8/23–23	F	61 17.9	16.934	14.098	–13.2	11.2	12	61 20.5	16.931	13.765	– 9.6	11.1
2386066.0	1820/ 9/22– 7	F	61 22.1	17.019	13.392	0.2	0.3	– 9	61 23.5	17.022	13.430	– 2.5	0.5
2386228.4	1821/ 3/ 4– 6	N	61 5.3	17.021	13.465	– 6.6	– 6.5	20	61 12.2	17.015	13.339	– 0.5	– 6.2
2386258.0	1821/ 4/ 2–15	N	61 24.9	17.038	13.665	7.3	5.0	– 2	61 25.0	17.037	13.630	6.7	4.9
2386287.5	1821/ 5/ 2– 0	N	60 57.4	16.837	14.915	19.4	15.2	–25	61 6.8	16.815	14.075	13.4	14.9
2386449.9	1821/10/11– 8	F	61 22.2	17.011	13.890	10.2	– 6.9	12	61 24.4	16.997	14.229	13.4	– 7.1
2386479.4	1821/11/ 9–18	F	61 24.4	17.052	15.613	21.6	–16.9	–10	61 26.3	17.048	15.201	19.5	–16.8
2386641.9	1822/ 4/21–16	N	61 7.3	16.905	14.561	16.2	11.8	19	61 13.3	16.907	15.347	20.4	12.1
2386671.4	1822/ 5/21– 0	N	61 24.0	16.935	16.476	24.8	20.0	– 3	61 24.1	16.933	16.385	24.5	20.0
2386863.3	1822/11/28–20	F	61 26.1	17.072	16.810	25.7	–21.3	9	61 27.6	17.072	17.017	26.4	–21.4
2386892.9	1822/12/28– 6	F	61 22.1	17.117	16.846	26.0	–23.3	–12	61 24.9	17.101	17.069	26.7	–23.3
2387055.3	1823/ 6/ 9– 0	N	61 5.2	16.852	16.851	26.2	22.8	19	61 11.2	16.872	16.829	25.9	22.9
2387084.8	1823/ 7/ 8– 7	N	61 21.5	16.960	16.327	23.7	22.6	– 3	61 21.6	16.959	16.408	24.0	22.6
2387276.8	1824/ 1/16– 9	F	61 27.1	17.148	15.737	20.5	–21.1	7	61 28.0	17.144	15.503	19.2	–21.0
2387306.3	1824/ 2/14–20	F	61 17.8	17.042	14.196	10.2	–13.1	–16	61 21.7	17.042	14.618	13.9	–13.4
2387468.7	1824/ 7/26– 7	N	61 5.8	16.883	15.096	17.4	19.5	19	61 11.8	16.863	14.561	13.4	19.3
2387498.3	1824/ 8/24–14	N	61 23.6	16.961	14.111	7.2	11.0	– 2	61 23.8	16.965	14.156	7.9	11.0
2387690.2	1825/ 3/ 4–21	F	61 28.7	17.052	14.039	1.8	– 6.3	5	61 29.1	17.049	14.030	0.6	– 6.2
2387719.7	1825/ 4/ 3– 6	F	61 14.7	16.933	14.350	– 9.6	5.2	–16	61 19.5	16.910	14.115	– 5.5	4.9
2387882.1	1825/ 9/12–15	N	61 9.5	16.902	13.979	– 0.4	4.2	18	61 15.1	16.877	14.119	– 4.9	3.9
2387911.7	1825/10/11–23	N	61 25.8	17.036	14.664	–11.0	– 7.2	– 3	61 26.1	17.035	14.596	–10.3	– 7.1
2388103.6	1826/ 4/22– 7	F	61 25.7	16.996	15.193	–14.6	12.0	4	61 25.9	16.999	15.280	–15.2	12.1
2388133.2	1826/ 5/21–15	F	61 9.7	16.891	16.060	–20.4	20.1	–18	61 15.1	16.877	15.755	–18.6	20.0
2388295.6	1826/10/31– 1	N	61 12.4	17.027	15.266	–15.3	–13.9	17	61 17.1	17.015	15.678	–17.6	–14.1
2388325.1	1826/11/29–11	N	61 25.8	17.124	16.256	–20.2	–21.4	– 5	61 26.3	17.125	16.198	–20.0	–21.4
2388517.1	1827/ 6/ 9–16	F	61 24.6	16.935	16.257	–20.0	22.9	3	61 24.8	16.934	16.260	–20.0	22.9
2388546.6	1827/ 7/ 8–23	F	61 9.8	16.819	15.748	–18.0	22.5	–18	61 15.2	16.822	16.046	–19.3	22.6
2388709.0	1827/12/18–14	N	61 18.6	17.077	16.141	–19.4	–23.4	14	61 22.1	17.054	16.080	–18.9	–23.4
2388738.5	1828/ 1/17– 1	N	61 26.4	17.078	15.633	–16.0	–21.0	– 8	61 27.5	17.074	15.781	–16.9	–21.0
2388930.5	1828/ 7/26–22	F	61 25.7	16.902	15.449	–14.5	19.3	4	61 25.9	16.901	15.388	–14.1	19.3
2388960.0	1828/ 8/25– 6	F	61 10.3	16.893	14.610	– 7.3	10.8	–18	61 15.8	16.885	14.911	–10.5	11.0
2389122.4	1829/ 2/ 4– 3	N	61 20.6	17.068	15.165	–12.4	–16.3	11	61 23.1	17.068	14.986	–10.5	–16.2
2389152.0	1829/ 3/ 5–13	N	61 21.6	17.066	14.574	– 4.1	– 6.0	–10	61 23.4	17.053	14.673	– 6.1	– 6.2
2389343.9	1829/ 9/13– 6	F	61 25.7	17.013	14.585	– 3.2	3.9	4	61 25.9	17.012	14.571	– 2.6	3.8
2389373.4	1829/10/12–15	F	61 9.2	16.991	14.552	5.8	– 7.5	–18	61 15.2	16.993	14.474	2.2	– 7.2
2389535.9	1830/ 3/24–15	N	61 19.7	17.049	14.486	0.2	1.4	10	61 21.5	17.050	14.519	2.2	1.5
2389565.4	1830/ 4/22–23	N	61 18.0	16.962	14.809	8.9	12.3	–11	61 20.2	16.957	14.677	6.8	12.1
2389727.8	1830/10/ 2– 8	F	61 0.8	16.899	14.311	1.1	– 3.4	24	61 10.1	16.862	14.520	5.9	– 3.8
2389757.3	1830/10/31–17	F	61 29.7	17.063	14.952	10.0	–14.1	2	61 29.8	17.062	14.981	10.3	–14.1

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2389786.9	1830/11/30– 3	F	61 9.3	17.015	15.610	16.6	–21.6	–20	61 16.3	16.987	15.300	14.2	–21.4
2389949.3	1831/ 5/12– 0	N	61 20.0	16.927	15.161	13.1	17.9	9	61 21.5	16.931	15.355	14.5	18.0
2389978.8	1831/ 6/10– 7	N	61 16.8	16.900	15.924	18.4	22.9	–12	61 19.2	16.886	15.758	17.3	22.9
2390141.2	1831/11/19–19	F	61 6.9	16.967	15.186	14.6	–19.4	22	61 14.7	16.944	15.688	17.5	–19.6
2390170.8	1831/12/19– 5	F	61 30.8	17.129	16.217	19.6	–23.4	0	61 30.8	17.128	16.212	19.6	–23.4
2390200.3	1832/ 1/17–16	F	61 3.4	17.033	15.941	19.4	–20.8	–23	61 12.2	16.998	16.180	20.2	–21.0
2390362.7	1832/ 6/28– 7	N	61 17.6	16.926	16.291	20.9	23.3	9	61 19.2	16.932	16.321	21.0	23.3
2390392.2	1832/ 7/27–14	N	61 14.9	16.936	15.935	19.2	19.2	–12	61 17.3	16.943	16.143	20.2	19.3
2390554.7	1833/ 1/ 6– 8	F	61 10.5	17.077	16.326	21.7	–22.5	19	61 16.8	17.061	16.200	20.9	–22.4
2390584.2	1833/ 2/ 4–19	F	61 29.1	17.127	15.720	17.9	–16.1	– 3	61 29.3	17.129	15.797	18.4	–16.1
2390776.1	1833/ 8/15–15	N	61 19.4	16.954	15.393	17.0	14.0	9	61 20.9	16.940	15.151	15.4	13.9
2390805.7	1833/ 9/13–22	N	61 17.4	16.947	14.307	7.9	3.6	–12	61 19.9	16.959	14.552	10.6	3.8
2390968.1	1834/ 2/23–21	F	61 15.0	17.030	14.774	13.9	– 9.7	17	61 19.9	17.007	14.410	10.2	– 9.5
2390997.6	1834/ 3/25– 6	F	61 28.1	17.006	14.034	2.9	1.6	– 5	61 28.5	17.004	14.075	4.2	1.6
2391189.6	1834/10/ 2–23	N	61 22.9	16.990	13.867	0.7	– 3.7	9	61 24.1	16.985	13.884	– 1.5	– 3.8
2391219.1	1834/11/ 1– 8	N	61 17.7	17.055	14.345	–11.2	–14.3	–13	61 20.8	17.044	14.091	– 7.9	–14.2
2391381.5	1835/ 4/13– 7	F	61 14.2	16.946	13.825	– 5.3	8.8	16	61 18.5	16.956	14.121	– 9.5	9.0
2391411.1	1835/ 5/12–15	F	61 23.9	16.971	14.982	–16.6	18.0	– 6	61 24.5	16.966	14.793	–15.3	18.0
2391603.0	1835/11/20–11	N	61 24.9	17.111	15.386	–19.4	–19.6	6	61 25.6	17.107	15.646	–20.7	–19.7
2391632.5	1835/12/19–21	N	61 15.3	17.084	16.817	–25.9	–23.4	–15	61 19.4	17.078	16.490	–24.5	–23.4
2391795.0	1836/ 5/30–16	F	61 13.3	16.902	16.103	–23.5	21.8	15	61 17.3	16.899	16.634	–25.5	21.9
2391824.5	1836/ 6/28–23	F	61 23.5	16.903	17.136	–27.0	23.2	– 6	61 24.1	16.906	17.120	–26.9	23.3
2392016.4	1837/ 1/ 7– 0	N	61 28.6	17.099	17.111	–27.0	–22.4	4	61 28.9	17.096	17.033	–26.7	–22.4
2392046.0	1837/ 2/ 5–10	N	61 12.8	17.018	15.347	–20.6	–15.9	–18	61 18.2	16.988	16.116	–23.8	–16.1
2392208.4	1837/ 7/17–23	F	61 14.7	16.841	16.630	–26.0	21.1	15	61 18.7	16.829	16.102	–23.9	21.0
2392237.9	1837/ 8/16– 6	F	61 24.7	16.930	14.917	–18.0	13.8	– 6	61 25.3	16.928	15.158	–19.4	13.9
2392429.9	1838/ 2/24–12	N	61 27.0	17.085	14.105	–12.5	– 9.5	2	61 27.1	17.087	14.051	–12.0	– 9.5
2392459.4	1838/ 3/25–22	N	61 5.8	16.975	13.295	1.2	1.9	–21	61 12.6	16.947	13.428	– 4.9	1.6
2392621.8	1838/ 9/ 4– 6	F	61 14.9	16.931	13.698	– 9.3	-7.3	15	61 18.7	16.926	13.459	– 4.8	7.1
2392651.3	1838/10/ 3–15	F	61 24.6	17.048	13.484	4.4	– 3.9	– 7	61 25.3	17.049	13.436	2.5	– 3.8
2392813.8	1839/ 3/15–14	N	60 59.9	16.979	13.254	– 2.3	– 2.2	23	61 8.5	16.977	13.380	4.6	– 1.9
2392843.3	1839/ 4/13–23	N	61 24.5	17.024	13.970	11.4	9.1	1	61 24.5	17.024	13.980	11.5	9.1
2392872.8	1839/ 5/13– 7	N	61 2.4	16.850	15.556	22.4	18.2	–21	61 9.9	16.834	14.694	17.7	18.0
2393035.2	1839/10/22–17	F	61 19.9	17.017	14.268	14.3	–11.0	13	61 23.0	17.000	14.803	17.8	–11.2
2393064.8	1839/11/21– 2	F	61 27.0	17.074	16.272	24.4	–19.7	– 8	61 28.2	17.071	15.950	23.1	–19.7
2393227.2	1840/ 5/ 2– 0	N	61 1.8	16.861	15.061	19.8	15.3	22	61 9.7	16.866	16.028	23.9	15.6
2393256.7	1840/ 5/31– 7	N	61 24.0	16.926	16.954	26.8	21.9	0	61 24.0	16.926	16.954	26.8	21.9
2393286.2	1840/ 6/29–14	N	61 1.5	16.825	16.848	27.1	23.2	–22	61 9.2	16.808	17.137	27.9	23.3
2393448.7	1840/12/ 9– 4	F	61 24.0	17.073	17.151	27.3	–22.8	12	61 26.2	17.071	17.231	27.5	–22.9
2393478.2	1841/ 1/ 7–15	F	61 24.7	17.124	16.503	25.0	–22.3	–10	61 26.6	17.112	16.841	26.2	–22.4
2393640.6	1841/ 6/19– 7	N	61 0.0	16.818	16.884	26.8	23.4	22	61 7.8	16.836	16.532	25.3	23.4
2393670.1	1841/ 7/18–14	N	61 21.9	16.963	15.874	22.2	21.0	0	61 21.9	16.963	15.869	22.2	21.0
2393699.7	1841/ 8/16–22	N	61 0.0	16.868	14.090	12.3	13.6	–22	61 7.8	16.893	14.869	17.6	13.9
2393862.1	1842/ 1/26–18	F	61 25.1	17.137	15.155	18.1	–18.7	9	61 26.6	17.130	14.848	16.1	–18.6
2393891.6	1842/ 2/25– 4	F	61 20.6	17.041	13.841	6.3	– 9.2	–13	61 23.4	17.042	14.104	9.8	– 9.4

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2394054.0	1842/ 8/ 6–15	N	61 1.1	16.866	14.553	14.8	16.7	22	61 8.9	16.838	14.027	9.4	16.5
2394083.6	1842/ 9/ 4–22	N	61 24.6	16.979	13.836	3.4	7.1	0	61 24.6	16.979	13.836	3.4	7.1
2394113.1	1842/10/ 4– 7	N	61 2.1	16.909	13.964	– 8.8	– 4.2	–22	61 10.1	16.913	13.739	– 3.0	– 3.8
2394275.5	1843/ 3/16– 6	F	61 26.7	17.030	13.933	– 2.5	– 2.0	7	61 27.6	17.026	13.992	– 4.3	– 1.9
2394305.1	1843/ 4/14–15	F	61 17.9	16.932	14.701	–13.7	9.3	–15	61 21.5	16.913	14.362	–10.4	9.1
2394467.5	1843/ 9/23–23	N	61 5.4	16.897	13.937	– 4.7	– 0.1	21	61 12.5	16.866	14.301	– 9.7	– 0.4
2394497.0	1843/10/23– 8	N	61 27.0	17.051	15.056	–15.1	–11.2	– 1	61 27.0	17.051	15.027	–14.9	–11.2
2394526.5	1843/11/21–18	N	60 59.6	17.017	16.115	–22.0	–19.9	–24	61 8.9	16.982	15.600	–19.2	–19.7
2394688.9	1844/ 5/ 2–15	F	61 23.9	16.971	15.633	–18.1	15.5	6	61 24.6	16.977	15.796	–19.0	15.6
2394718.5	1844/ 5/31–23	F	61 13.6	16.903	16.403	–22.3	22.0	–15	61 17.5	16.892	16.249	–21.5	21.9
2394880.9	1844/11/10–10	N	61 8.8	17.025	15.696	–18.7	–17.2	19	61 14.9	17.010	16.127	–20.6	–17.5
2394910.4	1844/12/ 9–20	N	61 27.1	17.134	16.473	–21.7	–22.9	– 3	61 27.3	17.135	16.472	–21.7	–22.9
2395102.4	1845/ 6/19–23	F	61 23.2	16.925	16.272	–20.6	23.4	6	61 23.8	16.922	16.216	–20.3	23.4
2395131.9	1845/ 7/19– 6	F	61 14.1	16.846	15.446	–16.4	20.9	–15	61 18.1	16.851	15.800	–18.4	21.0
2395294.3	1845/12/28–23	N	61 15.3	17.071	16.014	–19.2	–23.2	16	61 19.9	17.042	15.793	–17.8	–23.2
2395323.9	1846/ 1/27– 9	N	61 27.7	17.077	15.235	–13.7	–18.5	– 5	61 28.3	17.074	15.361	–14.6	–18.6
2395515.8	1846/ 8/ 7– 6	F	61 24.8	16.905	15.055	–11.8	16.5	6	61 25.4	16.903	14.950	–10.8	16.5
2395545.3	1846/ 9/ 5–13	F	61 14.9	16.932	14.416	– 3.4	6.8	–15	61 18.9	16.924	14.578	– 6.4	7.1
2395707.8	1847/ 2/15–11	N	61 17.2	17.047	14.769	– 8.9	–12.8	14	61 20.6	17.047	14.619	– 6.3	–12.6
2395737.3	1847/ 3/16–21	N	61 23.1	17.058	14.489	0.2	– 1.7	– 8	61 24.1	17.048	14.504	– 1.4	– 1.8
2395929.2	1847/ 9/24–14	F	61 25.2	17.025	14.534	1.1	– 0.4	6	61 25.7	17.024	14.554	2.2	– 0.4
2395958.8	1847/10/24– 0	F	61 13.8	17.030	14.858	9.8	–11.5	–17	61 18.5	17.030	14.677	6.9	–11.2
2396121.2	1848/ 4/ 3–23	N	61 16.4	17.020	14.557	4.5	5.6	12	61 19.1	17.023	14.694	6.8	5.8
2396150.7	1848/ 5/ 3– 7	N	61 20.0	16.960	15.176	12.3	15.7	– 9	61 21.4	16.957	15.034	10.9	15.6
2396342.7	1848/11/11– 2	F	61 29.6	17.077	15.336	13.2	–17.4	4	61 29.9	17.074	15.409	13.8	–17.5
2396372.2	1848/12/10–12	F	61 13.8	17.039	15.913	18.0	–23.0	–18	61 19.4	17.015	15.733	16.6	–22.9
2396534.6	1849/ 5/22– 8	N	61 16.9	16.901	15.517	15.5	20.4	12	61 19.3	16.905	15.737	16.8	20.5
2396564.1	1849/ 6/20–14	N	61 19.4	16.906	16.084	18.8	23.4	– 9	61 20.8	16.897	16.031	18.4	23.4
2396726.6	1849/11/30– 3	F	61 2.2	16.961	15.534	16.7	–21.6	24	61 11.6	16.931	15.955	18.7	–21.8
2396756.1	1849/12/29–14	F	61 30.8	17.129	16.259	19.4	–23.2	2	61 30.8	17.130	16.259	19.4	–23.2
2396785.6	1850/ 1/28– 1	F	61 8.0	17.043	15.608	16.9	–18.3	–21	61 15.2	17.016	15.977	18.7	–18.5
2396948.0	1850/ 7/ 9–14	N	61 14.9	16.912	16.161	19.9	22.4	13	61 17.4	16.916	16.079	19.4	22.3
2396977.6	1850/ 8/ 7–22	N	61 17.9	16.959	15.548	16.4	16.4	–10	61 19.4	16.966	15.743	17.5	16.5
2397140.0	1851/ 1/17–17	F	61 5.9	17.057	16.024	20.0	–20.8	21	61 13.7	17.037	15.717	18.0	–20.6
2397169.5	1851/ 2/16– 3	F	61 29.2	17.118	15.259	14.4	–12.5	– 1	61 29.2	17.119	15.283	14.5	–12.6
2397199.0	1851/ 3/17–13	F	61 2.5	16.907	14.220	5.1	– 1.4	–23	61 11.2	16.893	14.614	10.0	– 1.8
2397361.5	1851/ 8/26–22	N	61 17.2	16.956	14.948	13.3	10.4	12	61 19.6	16.937	14.704	11.0	10.2
2397391.0	1851/ 9/25– 6	N	61 20.7	16.977	14.216	3.6	– 0.6	– 9	61 22.3	16.986	14.320	5.8	– 0.5
2397553.4	1852/ 3/ 6– 5	F	61 10.4	16.995	14.400	9.7	– 5.6	19	61 16.7	16.971	14.160	5.3	– 5.3
2397582.9	1852/ 4/ 4–14	F	61 28.5	16.992	14.114	– 1.3	5.9	– 2	61 28.6	16.991	14.108	– 0.6	5.9
2397774.9	1852/10/13– 7	N	61 21.2	16.996	14.008	– 3.4	– 7.9	11	61 23.2	16.988	14.135	– 6.1	– 8.0
2397804.4	1852/11/11–17	N	61 21.1	17.078	14.857	–14.4	–17.6	–11	61 23.2	17.069	14.584	–12.0	–17.5
2397966.8	1853/ 4/23–15	F	61 9.5	16.905	14.129	– 9.1	12.6	18	61 15.2	16.918	14.609	–13.4	12.9
2397996.4	1853/ 5/22–23	F	61 24.7	16.962	15.504	–18.9	20.5	– 3	61 24.8	16.959	15.398	–18.3	20.5
2398188.3	1853/11/30–19	N	61 23.5	17.115	15.920	–21.5	–21.7	9	61 24.8	17.110	16.217	–22.8	–21.8

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2398217.9	1853/12/30– 6	N	61 18.6	17.096	16.892	–25.6	–23.2	–13	61 21.7	17.092	16.808	–25.2	–23.2
2398380.3	1854/ 6/10–23	F	61 8.8	16.869	16.455	–24.7	23.0	19	61 14.4	16.864	16.864	–26.0	23.1
2398409.8	1854/ 7/10– 6	F	61 24.8	16.912	16.953	–26.0	22.3	– 3	61 24.9	16.914	16.991	–26.1	22.3
2398601.8	1855/ 1/18– 9	N	61 27.3	17.094	16.660	–25.2	–20.6	6	61 28.0	17.089	16.475	–24.4	–20.6
2398631.3	1855/ 2/16–19	N	61 16.1	17.019	14.789	–16.9	–12.3	–16	61 20.3	16.995	15.429	–20.3	–12.5
2398793.7	1855/ 7/29– 6	F	61 10.7	16.826	16.061	–23.7	18.9	18	61 16.1	16.809	15.377	–20.5	18.7
2398823.2	1855/ 8/27–13	F	61 26.3	16.949	14.432	–14.4	10.2	– 3	61 26.5	16.948	14.542	–15.2	10.2
2399015.2	1856/ 3/ 6–21	N	61 25.7	17.068	13.758	– 8.3	– 5.3	4	61 26.0	17.072	13.685	– 7.1	– 5.3
2399044.7	1856/ 4/ 5– 6	N	61 9.6	16.978	13.474	5.4	6.2	–18	61 14.9	16.955	13.384	0.1	5.9
2399207.1	1856/ 9/14–14	F	61 11.4	16.926	13.445	– 5.2	3.2	18	61 16.5	16.920	13.370	0.1	2.9
2399236.7	1856/10/13–23	F	61 26.5	17.072	13.740	8.6	– 8.1	– 4	61 26.8	17.073	13.664	7.4	– 8.1
2399428.6	1857/ 4/24– 7	N	61 23.5	17.008	14.413	15.2	12.9	3	61 23.6	17.009	14.521	16.0	12.9
2399458.1	1857/ 5/23–15	N	61 7.0	16.862	16.180	24.9	20.6	–19	61 12.8	16.853	15.424	21.4	20.5
2399620.6	1857/11/ 2– 1	F	61 17.0	17.020	14.782	18.0	–14.7	16	61 21.2	16.998	15.498	21.6	–14.9
2399650.1	1857/12/ 1–11	F	61 29.1	17.090	16.854	26.6	–21.8	– 6	61 29.7	17.089	16.657	25.9	–21.8
2399842.0	1858/ 6/11–15	N	61 23.3	16.916	17.258	28.0	23.1	2	61 23.5	16.917	17.287	28.1	23.1
2399871.6	1858/ 7/10–22	N	61 6.5	16.853	16.554	26.1	22.2	–19	61 12.4	16.842	17.088	27.8	22.3
2400034.0	1858/12/20–13	F	61 21.3	17.069	17.246	27.9	–23.4	14	61 24.5	17.064	17.107	27.3	–23.4
2400063.5	1859/ 1/19– 0	F	61 26.6	17.126	15.974	23.1	–20.5	– 9	61 27.9	17.117	16.326	24.5	–20.5
2400255.5	1859/ 7/29–22	N	61 21.8	16.967	15.321	20.0	18.7	3	61 21.9	16.966	15.207	19.4	18.7
2400285.0	1859/ 8/28– 5	N	61 5.4	16.912	13.723	8.7	9.9	–19	61 11.4	16.933	14.271	13.9	10.2
2400447.4	1860/ 2/ 7– 2	F	61 22.5	17.119	14.560	15.0	–15.6	11	61 24.7	17.111	14.233	12.2	–15.4
2400476.9	1860/ 3/ 7–13	F	61 22.9	17.037	13.620	2.2	– 5.0	–11	61 24.8	17.039	13.730	5.3	– 5.2
2400668.9	1860/ 9/15– 6	N	61 24.9	16.995	13.692	– 0.7	2.9	3	61 25.0	16.992	13.698	– 1.4	2.9
2400698.4	1860/10/14–15	N	61 7.5	16.951	14.305	–13.0	– 8.4	–20	61 13.9	16.951	13.898	– 8.0	– 8.1
2400860.8	1861/ 3/26–14	F	61 24.2	17.003	13.985	– 6.8	2.3	9	61 25.7	16.999	14.163	– 9.2	2.5
2400890.4	1861/ 4/24–22	F	61 20.7	16.930	15.180	–17.6	13.1	–12	61 23.1	16.915	14.803	–15.0	12.9
2401052.8	1861/10/ 4– 7	N	61 0.9	16.891	14.046	– 8.9	– 4.4	23	61 9.7	16.853	14.676	–14.4	– 4.7
2401082.3	1861/11/ 2–16	N	61 27.6	17.064	15.562	–18.9	–14.9	1	61 27.6	17.064	15.599	–19.1	–14.9
2401111.9	1861/12/ 2– 2	N	61 4.8	17.048	16.535	–24.1	–21.9	–21	61 12.4	17.015	16.214	–22.5	–21.8
2401274.3	1862/ 5/13–23	F	61 21.5	16.944	16.098	–21.2	18.5	9	61 22.9	16.952	16.308	–22.1	18.6
2401303.8	1862/ 6/12– 6	F	61 16.9	16.913	16.589	–23.5	23.1	–12	61 19.6	16.906	16.601	–23.4	23.1
2401466.2	1862/11/21–18	N	61 4.8	17.021	16.113	–21.5	–20.0	22	61 12.3	17.001	16.443	–22.6	–20.2
2401495.8	1862/12/21– 5	N	61 27.8	17.140	16.484	–22.2	–23.4	– 1	61 27.9	17.141	16.499	–22.3	–23.4
2401525.3	1863/ 1/19–16	N	60 59.8	17.000	15.195	–16.8	–20.3	–24	61 9.1	16.974	15.879	–20.2	–20.5
2401687.7	1863/ 7/ 1– 7	F	61 21.2	16.915	16.103	–20.3	23.1	8	61 22.6	16.908	15.939	–19.5	23.1
2401717.2	1863/ 7/30–14	F	61 17.9	16.873	15.059	–14.2	18.6	–13	61 20.6	16.880	15.385	–16.3	18.7
2401879.6	1864/ 1/ 9– 8	N	61 11.5	17.058	15.700	–18.2	–22.2	18	61 17.3	17.024	15.334	–15.7	–22.1
2401909.2	1864/ 2/ 7–18	N	61 28.5	17.072	14.814	–10.6	–15.3	– 4	61 28.7	17.071	14.889	–11.3	–15.4
2402101.1	1864/ 8/17–14	F	61 23.2	16.907	14.673	– 8.6	13.2	8	61 24.5	16.903	14.560	– 6.9	13.1
2402130.7	1864/ 9/15–21	F	61 18.8	16.968	14.338	0.8	2.7	–12	61 21.7	16.960	14.371	– 1.9	2.9
2402293.1	1865/ 2/25–20	N	61 13.2	17.020	14.451	– 5.0	– 8.8	16	61 17.8	17.022	14.391	– 1.7	– 8.6
2402322.6	1865/ 3/27– 5	N	61 24.0	17.048	14.543	4.5	2.6	– 5	61 24.6	17.041	14.506	3.4	2.5
2402514.6	1865/10/ 4–23	F	61 24.2	17.034	14.619	5.4	– 4.6	7	61 25.2	17.033	14.710	6.9	– 4.8
2402544.1	1865/11/ 3– 8	F	61 17.9	17.064	15.253	13.4	–15.1	–14	61 21.3	17.062	15.033	11.3	–14.9

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2402706.5	1866/ 4/15– 7	N	61 12.4	16.986	14.751	8.6	9.7	15	61 16.4	16.991	15.008	11.1	9.9
2402736.0	1866/ 5/14–15	N	61 21.5	16.957	15.565	15.3	18.7	– 7	61 22.2	16.956	15.458	14.5	18.6
2402928.0	1866/11/22–10	F	61 29.0	17.087	15.714	15.9	–20.1	6	61 29.6	17.082	15.811	16.5	–20.2
2402957.5	1866/12/21–21	F	61 17.8	17.056	16.047	18.4	–23.4	–16	61 22.2	17.037	16.022	18.1	–23.4
2403119.9	1867/ 6/ 2–15	N	61 13.1	16.874	15.795	17.2	22.2	15	61 16.8	16.877	15.974	18.1	22.2
2403149.5	1867/ 7/ 1–22	N	61 21.3	16.911	16.072	18.4	23.1	– 7	61 22.1	16.907	16.095	18.5	23.1
2403341.4	1868/ 1/ 9–23	F	61 30.1	17.126	16.103	18.4	–22.1	3	61 30.3	17.127	16.072	18.2	–22.1
2403370.9	1868/ 2/ 8–10	F	61 12.0	17.049	15.232	13.8	–15.1	–19	61 17.8	17.028	15.616	16.1	–15.4
2403533.4	1868/ 7/19–22	N	61 11.5	16.897	15.878	18.2	20.7	15	61 15.2	16.899	15.679	16.9	20.6
2403562.9	1868/ 8/18– 5	N	61 20.3	16.981	15.167	13.0	13.0	– 6	61 21.0	16.986	15.299	14.0	13.1
2403725.3	1869/ 1/28– 1	F	61 0.8	17.031	15.599	17.5	–18.2	24	61 10.3	17.006	15.197	14.4	–17.9
2403754.8	1869/ 2/26–12	F	61 28.7	17.106	14.883	10.4	– 8.6	1	61 28.7	17.105	14.863	10.1	– 8.6
2403784.4	1869/ 3/27–22	F	61 7.0	16.912	14.225	0.8	2.9	–21	61 14.1	16.902	14.397	5.3	2.5
2403946.8	1869/ 9/ 6– 6	N	61 14.5	16.957	14.606	9.3	6.4	14	61 18.0	16.932	14.421	6.2	6.2
2403976.3	1869/10/ 5–14	N	61 23.5	17.004	14.270	– 0.6	– 4.9	– 7	61 24.4	17.010	14.281	1.0	– 4.8
2404138.7	1870/ 3/17–14	F	61 5.2	16.955	14.178	5.3	– 1.3	21	61 13.1	16.931	14.115	0.3	– 0.9
2404168.3	1870/ 4/15–22	F	61 28.2	16.975	14.329	– 5.3	9.9	0	61 28.2	16.975	14.326	– 5.2	9.9
2404197.8	1870/ 5/15– 6	F	61 4.3	16.832	14.974	–14.7	18.8	–22	61 12.1	16.797	14.530	–10.4	18.6
2404360.2	1870/10/24–16	N	61 19.0	17.000	14.280	– 7.3	–11.8	13	61 21.8	16.990	14.535	–10.3	–12.0
2404389.7	1870/11/23– 1	N	61 23.8	17.097	15.382	–17.0	–20.3	– 8	61 25.2	17.089	15.149	–15.4	–20.2
2404552.2	1871/ 5/ 4–23	F	61 4.2	16.860	14.514	–12.4	16.0	21	61 11.7	16.877	15.149	–16.7	16.3
2404581.7	1871/ 6/ 3– 7	F	61 24.8	16.952	15.951	–20.6	22.3	– 1	61 24.8	16.952	15.934	–20.5	22.3
2404611.2	1871/ 7/ 2–14	F	61 1.1	16.817	16.503	–23.9	23.0	–23	61 9.3	16.817	16.338	–22.9	23.1
2404773.6	1871/12/12– 4	N	61 21.6	17.115	16.323	–22.8	–23.0	11	61 23.6	17.109	16.579	–23.8	–23.1
2404803.2	1872/ 1/10–15	N	61 21.4	17.103	16.719	–24.4	–22.0	–11	61 23.6	17.101	16.814	–24.7	–22.1
2404965.6	1872/ 6/21– 7	F	61 3.8	16.836	16.616	–25.0	23.4	21	61 11.2	16.827	16.788	–25.4	23.4
2404995.1	1872/ 7/20–14	F	61 25.4	16.921	16.585	–24.2	20.5	– 1	61 25.4	16.921	16.597	–24.2	20.6
2405024.7	1872/ 8/18–21	F	61 2.7	16.815	14.961	–17.4	12.8	–22	61 10.9	16.824	15.789	–21.4	13.1
2405187.1	1873/ 1/28–17	N	61 25.4	17.084	16.077	–22.5	–18.0	9	61 26.6	17.077	15.792	–21.2	–17.9
2405216.6	1873/ 2/27– 3	N	61 19.0	17.017	14.349	–12.9	– 8.3	–13	61 22.1	16.998	14.804	–16.1	– 8.5
2405379.0	1873/ 8/ 8–14	F	61 6.0	16.811	15.446	–20.8	16.0	21	61 13.2	16.787	14.708	–16.4	15.8
2405408.6	1873/ 9/ 6–21	F	61 27.3	16.966	14.074	–10.4	6.2	0	61 27.3	16.966	14.089	–10.5	6.2
2405438.1	1873/10/ 6– 6	F	61 2.2	16.943	13.442	2.6	– 5.1	–23	61 10.9	16.925	13.540	– 3.9	– 4.8
2405600.5	1874/ 3/18– 5	N	61 23.8	17.047	13.582	– 4.0	– 1.0	6	61 24.5	17.053	13.543	– 2.1	– 0.9
2405630.0	1874/ 4/16–14	N	61 12.9	16.981	13.804	9.4	10.2	–15	61 16.9	16.961	13.558	5.0	10.0
2405792.5	1874/ 9/25–22	F	61 7.4	16.921	13.352	– 1.0	– 1.1	20	61 14.0	16.912	13.499	5.1	– 1.4
2405822.0	1874/10/25– 7	F	61 27.8	17.093	14.149	12.5	–12.1	– 1	61 27.9	17.093	14.098	12.0	–12.1
2405851.5	1874/11/23–18	F	60 59.4	16.997	15.781	23.4	–20.4	–25	61 9.2	16.980	14.835	18.3	–20.2
2406013.9	1875/ 5/ 5–15	N	61 21.9	16.990	14.953	18.6	16.2	5	61 22.4	16.991	15.188	19.8	16.3
2406043.5	1875/ 6/ 3–22	N	61 11.0	16.874	16.701	26.6	22.3	–16	61 15.3	16.870	16.151	24.4	22.3
2406205.9	1875/11/13–10	F	61 13.6	17.020	15.378	21.3	–17.9	18	61 19.1	16.993	16.203	24.6	–18.1
2406235.4	1875/12/12–20	F	61 30.5	17.102	17.254	27.9	–23.1	– 4	61 30.8	17.102	17.176	27.6	–23.1
2406427.4	1876/ 6/21–22	N	61 22.1	16.906	17.334	28.4	23.4	6	61 22.6	16.907	17.303	28.2	23.4
2406456.9	1876/ 7/21– 5	N	61 11.0	16.879	16.093	24.4	20.4	–16	61 15.3	16.873	16.723	26.6	20.5
2406619.3	1876/12/30–22	F	61 18.1	17.061	17.061	27.5	–23.1	15	61 22.3	17.052	16.658	26.0	–23.0

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2406648.8	1877/ 1/29– 9	F	61 28.1	17.123	15.351	20.5	–17.8	– 7	61 28.8	17.118	15.638	21.8	–17.9
2406840.8	1877/ 8/ 9– 5	N	61 21.0	16.970	14.744	17.2	15.8	6	61 21.5	16.968	14.539	15.8	15.8
2406870.3	1877/ 9/ 7–13	N	61 10.2	16.952	13.471	4.8	5.9	–16	61 14.6	16.969	13.787	9.5	6.2
2407032.7	1878/ 2/17–11	F	61 19.3	17.096	14.031	11.4	–11.9	13	61 22.5	17.086	13.750	7.7	–11.7
2407062.3	1878/ 3/18–21	F	61 24.7	17.031	13.555	– 2.1	– 0.7	– 9	61 25.9	17.033	13.546	0.4	– 0.9
2407254.2	1878/ 9/26–14	N	61 24.7	17.009	13.701	– 5.0	– 1.3	5	61 25.1	17.002	13.768	– 6.3	– 1.4
2407283.7	1878/10/25–23	N	61 12.3	16.987	14.797	–17.0	–12.3	–17	61 17.3	16.984	14.278	–12.9	–12.1
2407446.2	1879/ 4/ 6–22	F	61 21.0	16.973	14.196	–11.1	6.6	12	61 23.4	16.968	14.540	–14.0	6.8
2407475.7	1879/ 5/ 6– 6	F	61 22.9	16.926	15.742	–21.0	16.4	– 9	61 24.4	16.915	15.401	–19.2	16.3
2407667.6	1879/11/14– 1	N	61 27.6	17.073	16.123	–22.1	–18.1	3	61 27.8	17.074	16.226	–22.6	–18.1
2407697.2	1879/12/13–11	N	61 9.4	17.072	16.770	–25.3	–23.1	–19	61 15.6	17.043	16.712	–24.9	–23.1
2407859.6	1880/ 5/24– 7	F	61 18.5	16.915	16.514	–23.6	20.8	11	61 20.8	16.925	16.698	–24.3	20.9
2407889.1	1880/ 6/22–14	F	61 19.6	16.923	16.577	–23.9	23.4	–10	61 21.3	16.919	16.716	–24.4	23.4
2408051.5	1880/12/ 2– 3	N	61 0.4	17.014	16.430	–23.5	–22.0	24	61 9.4	16.987	16.520	–23.6	–22.1
2408081.1	1880/12/31–14	N	61 28.0	17.143	16.270	–21.8	–23.0	1	61 28.0	17.142	16.252	–21.8	–23.0
2408110.6	1881/ 1/30– 1	N	61 4.5	17.009	14.743	–14.2	–17.7	–22	61 12.2	16.989	15.423	–18.3	–17.9
2408273.0	1881/ 7/11–14	F	61 18.7	16.904	15.767	–19.3	22.0	12	61 20.9	16.893	15.476	–17.6	22.0
2408302.6	1881/ 8/ 9–21	F	61 21.1	16.900	14.647	–11.4	15.6	–10	61 22.8	16.906	14.889	–13.4	15.8
2408465.0	1882/ 1/19–16	N	61 7.1	17.040	15.248	–16.3	–20.2	21	61 14.3	17.001	14.798	–12.6	–20.1
2408494.5	1882/ 2/18– 3	N	61 28.6	17.064	14.438	– 7.0	–11.7	– 2	61 28.7	17.063	14.462	– 7.4	–11.7
2408524.0	1882/ 3/19–12	N	60 59.9	16.917	14.094	3.6	– 0.5	–24	61 9.2	16.867	14.117	– 1.9	– 0.9
2408686.4	1882/ 8/28–21	F	61 21.1	16.909	14.355	– 5.0	9.5	11	61 23.2	16.902	14.289	– 2.5	9.4
2408716.0	1882/ 9/27– 5	F	61 22.2	17.000	14.395	5.1	– 1.6	–10	61 24.1	16.993	14.331	2.9	– 1.4
2408878.4	1883/ 3/ 9– 4	N	61 8.6	16.987	14.249	– 0.8	– 4.6	19	61 14.6	16.992	14.338	3.2	– 4.3
2408907.9	1883/ 4/ 7–14	N	61 24.4	17.036	14.735	8.8	6.8	– 4	61 24.6	17.031	14.687	8.1	6.8
2409099.9	1883/10/16– 7	F	61 22.6	17.042	14.837	9.6	– 8.8	10	61 24.3	17.040	15.023	11.4	– 8.9
2409129.4	1883/11/14–17	F	61 21.4	17.092	15.685	16.6	–18.3	–12	61 23.8	17.090	15.488	15.2	–18.1
2409291.8	1884/ 4/25–15	N	61 7.9	16.947	15.042	12.3	13.4	18	61 13.3	16.956	15.405	14.8	13.7
2409321.4	1884/ 5/24–23	N	61 22.4	16.953	15.911	17.6	21.0	– 4	61 22.7	16.953	15.862	17.3	20.9
2409513.3	1884/12/ 2–19	F	61 27.7	17.093	16.011	17.8	–22.1	8	61 28.8	17.085	16.089	18.2	–22.2
2409542.8	1885/ 1/ 1– 5	F	61 21.2	17.068	15.988	18.0	–23.0	–13	61 24.6	17.054	16.098	18.4	–23.0
2409705.3	1885/ 6/12–23	N	61 8.8	16.846	15.941	18.2	23.2	17	61 13.9	16.846	16.006	18.4	23.2
2409734.8	1885/ 7/12– 5	N	61 22.7	16.917	15.897	17.3	22.0	– 3	61 23.0	16.916	15.941	17.6	22.0
2409926.7	1886/ 1/20– 8	F	61 28.9	17.117	15.793	16.4	–20.1	5	61 29.4	17.118	15.710	15.9	–20.1
2409956.3	1886/ 2/18–18	F	61 15.5	17.051	14.891	10.1	–11.4	–16	61 20.1	17.035	15.202	12.7	–11.7
2410118.7	1886/ 7/31– 5	N	61 7.6	16.882	15.498	15.8	18.3	18	61 12.8	16.880	15.220	13.5	18.1
2410148.2	1886/ 8/29–13	N	61 22.1	17.001	14.847	9.2	9.3	– 4	61 22.4	17.004	14.909	9.9	9.3
2410340.2	1887/ 3/ 9–20	F	61 27.6	17.089	14.630	6.1	– 4.4	4	61 27.9	17.087	14.597	5.4	– 4.3
2410369.7	1887/ 4/ 8– 6	F	61 11.1	16.916	14.368	– 3.4	7.1	–19	61 16.7	16.908	14.363	0.4	6.8
2410532.1	1887/ 9/17–14	N	61 11.3	16.955	14.393	5.0	2.2	17	61 16.1	16.925	14.323	1.4	2.0
2410561.6	1887/10/16–23	N	61 25.6	17.027	14.460	– 4.7	– 9.0	– 5	61 26.0	17.031	14.427	– 3.7	– 9.0
2410724.1	1888/ 3/27–22	F	60 59.4	16.908	14.107	1.0	3.0	24	61 9.2	16.886	14.259	– 4.4	3.4
2410753.6	1888/ 4/26– 6	F	61 27.4	16.956	14.648	– 8.9	13.7	3	61 27.5	16.957	14.687	– 9.4	13.7
2410783.1	1888/ 5/25–14	F	61 9.0	16.846	15.437	–16.9	21.1	–19	61 15.1	16.817	15.037	–13.8	20.9
2410945.5	1888/11/ 4– 0	N	61 16.2	17.002	14.647	–10.9	–15.5	15	61 20.1	16.989	15.018	–13.9	–15.6

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2410975.1	1888/12/ 3–10	N	61 25.9	17.110	15.841	–18.9	–22.2	– 6	61 26.7	17.104	15.686	–18.0	–22.2
2411137.5	1889/ 5/15– 7	F	60 58.4	16.812	14.927	–15.2	18.9	24	61 7.8	16.832	15.640	–19.1	19.2
2411167.0	1889/ 6/13–14	F	61 24.4	16.942	16.259	–21.5	23.2	2	61 24.4	16.943	16.299	–21.7	23.2
2411196.5	1889/ 7/12–21	F	61 6.3	16.849	16.365	–22.6	21.9	–19	61 12.6	16.852	16.464	–22.8	22.0
2411359.0	1889/12/22–13	N	61 19.1	17.112	16.524	–23.2	–23.4	13	61 22.0	17.103	16.659	–23.7	–23.4
2411388.5	1890/ 1/21– 0	N	61 23.5	17.106	16.352	–22.3	–19.9	– 9	61 25.0	17.105	16.534	–23.1	–20.0
2411550.9	1890/ 7/ 2–14	F	60 58.2	16.801	16.561	–24.5	23.0	25	61 7.6	16.788	16.435	–23.7	22.9
2411580.4	1890/ 7/31–21	F	61 25.4	16.929	16.105	–21.7	18.1	3	61 25.5	16.927	16.042	–21.4	18.1
2411610.0	1890/ 8/30– 5	F	61 8.3	16.859	14.563	–13.6	9.0	–20	61 14.5	16.866	15.196	–17.6	9.3
2411772.4	1891/ 2/ 9– 2	N	61 22.9	17.069	15.466	–19.2	–14.8	10	61 24.8	17.060	15.127	–17.2	–14.7
2411801.9	1891/ 3/10–12	N	61 21.4	17.012	14.061	– 8.6	– 4.1	–12	61 23.6	16.998	14.333	–11.5	– 4.3
2411964.3	1891/ 8/19–21	F	61 0.9	16.796	14.864	–17.4	12.7	24	61 10.0	16.765	14.188	–11.8	12.3
2411993.9	1891/ 9/18– 5	F	61 27.7	16.981	13.865	– 6.2	2.0	2	61 27.7	16.981	13.840	– 5.7	2.0
2412023.4	1891/10/17–14	F	61 7.7	16.989	13.722	6.7	– 9.3	–20	61 14.6	16.969	13.589	1.1	– 9.0
2412185.8	1892/ 3/28–13	N	61 21.2	17.021	13.576	0.3	3.3	9	61 22.6	17.031	13.622	2.8	3.4
2412215.4	1892/ 4/26–22	N	61 15.8	16.981	14.258	13.1	13.9	–13	61 18.6	16.965	13.932	9.6	13.7
2412377.8	1892/10/ 6– 6	F	61 2.9	16.914	13.421	3.3	– 5.3	23	61 11.3	16.902	13.830	9.8	– 5.7
2412407.3	1892/11/ 4–16	F	61 28.5	17.109	14.678	16.1	–15.7	0	61 28.5	17.109	14.694	16.2	–15.7
2412436.8	1892/12/ 4– 2	F	61 4.8	17.028	16.367	25.2	–22.3	–22	61 12.9	17.014	15.588	21.7	–22.2
2412599.3	1893/ 5/15–23	N	61 19.7	16.969	15.529	21.4	19.1	8	61 20.8	16.971	15.881	22.9	19.2
2412628.8	1893/ 6/14– 6	N	61 14.5	16.886	17.045	27.5	23.3	–13	61 17.5	16.886	16.742	26.3	23.2
2412791.2	1893/11/23–18	F	61 9.7	17.017	15.976	23.9	–20.5	20	61 16.6	16.984	16.780	26.7	–20.7
2412820.7	1893/12/23– 5	F	61 31.4	17.109	17.394	28.2	–23.4	– 2	61 31.4	17.109	17.389	28.2	–23.4
2412850.3	1894/ 1/21–15	F	61 1.5	16.979	16.031	24.4	–19.8	–24	61 11.3	16.933	16.930	27.4	–20.0
2413012.7	1894/ 7/ 3– 6	N	61 20.3	16.896	17.166	27.9	23.0	8	61 21.4	16.896	16.993	27.3	22.9
2413042.2	1894/ 8/ 1–12	N	61 14.9	16.904	15.539	21.9	18.0	–13	61 17.8	16.901	16.129	24.3	18.1
2413204.6	1895/ 1/11– 7	F	61 14.3	17.048	16.622	26.3	–21.8	17	61 19.7	17.035	15.976	23.6	–21.7
2413234.2	1895/ 2/ 9–17	F	61 28.9	17.116	14.734	17.1	–14.6	– 4	61 29.3	17.113	14.916	18.2	–14.6
2413426.1	1895/ 8/20–13	N	61 19.7	16.972	14.214	13.8	12.4	8	61 20.8	16.969	13.971	11.6	12.3
2413455.6	1895/ 9/18–21	N	61 14.4	16.988	13.363	0.6	1.7	–13	61 17.6	17.002	13.478	4.7	1.9
2413618.1	1896/ 2/28–20	F	61 15.5	17.067	13.623	7.4	– 7.9	15	61 19.8	17.056	13.460	2.8	– 7.7
2413647.6	1896/ 3/29– 5	F	61 25.9	17.023	13.656	– 6.4	3.6	– 6	61 26.5	17.025	13.575	– 4.5	3.5
2413839.5	1896/10/ 6–22	N	61 23.9	17.021	13.875	– 9.2	– 5.6	7	61 24.8	17.010	14.055	–11.2	– 5.7
2413869.1	1896/11/ 5– 8	N	61 16.6	17.017	15.407	–20.6	–15.9	–15	61 20.3	17.013	14.859	–17.4	–15.7
2414031.5	1897/ 4/17– 6	F	61 17.2	16.938	14.555	–15.1	10.6	14	61 20.8	16.933	15.094	–18.4	10.8
2414061.0	1897/ 5/16–14	F	61 24.6	16.920	16.321	–23.9	19.2	– 7	61 25.4	16.913	16.076	–22.9	19.2
2414253.0	1897/11/24– 9	N	61 27.1	17.080	16.652	–24.7	–20.6	6	61 27.5	17.080	16.784	–25.2	–20.7
2414282.5	1897/12/23–20	N	61 13.5	17.090	16.761	–25.6	–23.4	–17	61 18.4	17.064	16.966	–26.2	–23.4
2414444.9	1898/ 6/ 4–14	F	61 14.9	16.886	16.803	–25.3	22.5	14	61 18.4	16.896	16.856	–25.4	22.5
2414474.4	1898/ 7/ 3–21	F	61 21.8	16.933	16.360	–23.4	22.9	– 7	61 22.7	16.931	16.550	–24.2	22.9
2414666.4	1899/ 1/11–23	N	61 27.5	17.141	15.860	–20.5	–21.7	3	61 27.7	17.140	15.773	–20.1	–21.7
2414695.9	1899/ 2/10– 9	N	61 8.6	17.014	14.298	–11.0	–14.3	–19	61 15.0	17.000	14.868	–15.4	–14.6
2414858.3	1899/ 7/22–22	F	61 15.6	16.893	15.309	–17.6	20.2	14	61 19.0	16.877	14.914	–14.9	20.1
2414887.9	1899/ 8/21– 5	F	61 23.7	16.926	14.268	– 8.1	12.2	– 7	61 24.6	16.931	14.408	– 9.8	12.3
2415050.3	1900/ 1/31– 1	N	61 2.1	17.015	14.730	–13.7	–17.5	23	61 10.9	16.972	14.292	– 8.7	–17.3

TABLE 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2415079.8	1900/ 3/ 1–11	N	61 28.2	17.052	14.161	– 3.0	– 7.6	1	61 28.2	17.052	14.158	– 2.9	– 7.6
2415109.4	1900/ 3/30–21	N	61 4.5	16.923	14.250	8.0	3.8	–22	61 12.1	16.880	14.064	2.9	3.5
2415271.8	1900/ 9/ 9– 5	F	61 18.4	16.910	14.141	– 1.0	5.5	14	61 21.6	16.899	14.182	2.2	5.3
2415301.3	1900/10/ 8–13	F	61 25.0	17.028	14.597	9.3	– 5.8	– 7	61 26.1	17.022	14.480	7.7	– 5.7
2415463.7	1901/ 3/20–13	N	61 3.4	16.948	14.184	3.5	– 0.3	21	61 11.0	16.957	14.472	8.0	0.0
2415493.2	1901/ 4/18–22	N	61 24.3	17.020	15.053	12.8	10.8	– 1	61 24.3	17.019	15.034	12.7	10.8
2415522.8	1901/ 5/18– 6	N	60 58.7	16.868	15.796	19.0	19.4	–23	61 7.3	16.849	15.404	16.4	19.2
2415685.2	1901/10/27–15	F	61 20.5	17.047	15.170	13.6	–12.7	13	61 23.1	17.044	15.451	15.4	–12.9
2415714.7	1901/11/26– 1	F	61 24.2	17.114	16.080	19.0	–20.8	– 9	61 25.9	17.113	15.954	18.3	–20.7
2415877.1	1902/ 5/ 7–23	N	61 2.8	16.905	15.388	15.7	16.7	20	61 9.8	16.916	15.795	17.8	17.0
2415906.7	1902/ 6/ 6– 6	N	61 22.8	16.949	16.153	19.2	22.6	– 1	61 22.8	16.949	16.146	19.1	22.5
2415936.2	1902/ 7/ 5–13	N	60 58.6	16.787	15.743	18.1	22.8	–23	61 7.2	16.792	16.021	19.2	22.9
2416098.6	1902/12/15– 4	F	61 26.0	17.095	16.159	18.9	–23.2	10	61 27.7	17.084	16.164	18.8	–23.2
2416128.2	1903/ 1/13–14	F	61 24.1	17.075	15.756	16.7	–21.6	–12	61 26.5	17.065	15.945	17.7	–21.7
2416290.6	1903/ 6/25– 6	N	61 3.9	16.817	15.925	18.5	23.4	21	61 10.8	16.812	15.819	17.6	23.4
2416320.1	1903/ 7/24–13	N	61 23.5	16.923	15.597	15.4	20.1	– 1	61 23.5	16.923	15.615	15.6	20.1
2416349.6	1903/ 8/22–20	N	60 58.7	16.853	14.664	8.9	12.0	–23	61 7.4	16.857	15.100	12.6	12.3
2416512.1	1904/ 2/ 1–17	F	61 27.1	17.104	15.396	13.7	–17.4	7	61 28.1	17.105	15.272	12.7	–17.3
2416541.6	1904/ 3/ 2– 3	F	61 18.5	17.050	14.639	6.0	– 7.4	–15	61 22.0	17.038	14.835	8.6	– 7.6
2416704.0	1904/ 8/11–13	N	61 3.2	16.867	15.085	12.8	15.3	20	61 10.1	16.860	14.802	9.5	15.1
2416733.5	1904/ 9/ 9–21	N	61 23.3	17.019	14.629	5.1	5.2	– 2	61 23.4	17.020	14.641	5.3	5.3
2416763.1	1904/10/ 9– 6	N	60 57.6	16.933	14.374	– 3.9	– 6.1	–24	61 6.9	16.947	14.381	0.7	– 5.7
2416925.5	1905/ 3/21– 5	F	61 26.0	17.068	14.516	1.8	0.0	5	61 26.6	17.065	14.508	0.6	0.1
2416955.0	1905/ 4/19–14	F	61 14.7	16.919	14.632	– 7.3	11.1	–16	61 19.0	16.914	14.506	– 4.2	10.8
2417117.4	1905/ 9/28–22	N	61 7.6	16.952	14.318	0.7	– 2.0	19	61 13.8	16.916	14.404	– 3.3	– 2.3
2417147.0	1905/10/28– 7	N	61 27.1	17.047	14.764	– 8.6	–12.9	– 2	61 27.3	17.048	14.731	– 8.1	–12.9
2417338.9	1906/ 5/ 8–14	F	61 25.9	16.935	15.029	–12.1	16.9	5	61 26.4	16.937	15.128	–12.9	17.0
2417368.4	1906/ 6/ 6–21	F	61 13.2	16.858	15.811	–18.3	22.6	–16	61 17.7	16.836	15.527	–16.4	22.5
2417530.9	1906/11/16– 9	N	61 13.0	17.003	15.060	–13.9	–18.6	17	61 18.1	16.985	15.496	–16.6	–18.7
2417560.4	1906/12/15–19	N	61 27.4	17.118	16.160	–19.9	–23.2	– 5	61 27.8	17.114	16.088	–19.5	–23.2
2417752.3	1907/ 6/25–21	F	61 23.3	16.931	16.387	–21.6	23.4	5	61 23.7	16.934	16.425	–21.7	23.4
2417781.9	1907/ 7/25– 5	F	61 11.0	16.881	16.075	–20.6	19.9	–17	61 15.6	16.885	16.328	–21.6	20.1
2417944.3	1908/ 1/ 3–22	N	61 16.1	17.104	16.493	–22.7	–22.9	15	61 19.9	17.092	16.453	–22.4	–22.8
2417973.8	1908/ 2/ 2– 9	N	61 25.2	17.105	15.879	–19.5	–17.2	– 8	61 26.0	17.105	16.064	–20.4	–17.2
2418165.8	1908/ 8/12– 5	F	61 24.9	16.938	15.591	–18.5	15.1	5	61 25.3	16.932	15.451	–17.7	15.0
2418195.3	1908/ 9/10–12	F	61 13.2	16.901	14.288	– 9.4	5.0	–16	61 17.9	16.906	14.703	–13.2	5.2
2418357.7	1909/ 2/20–11	N	61 19.8	17.049	14.919	–15.4	–11.0	12	61 22.6	17.039	14.587	–12.7	–10.9
2418387.2	1909/ 3/21–20	N	61 23.2	17.006	13.939	– 4.3	0.2	– 9	61 24.6	16.995	14.060	– 6.7	0.1
2418579.2	1909/ 9/29–13	F	61 27.5	16.994	13.815	– 1.9	– 2.3	4	61 27.8	16.994	13.804	– 0.7	– 2.4
2418608.7	1909/10/28–22	F	61 12.5	17.029	14.136	10.5	–13.1	–17	61 17.9	17.008	13.849	5.9	–12.9
2418771.1	1910/ 4/ 9–21	N	61 18.1	16.992	13.727	4.4	7.5	12	61 20.3	17.005	13.902	7.5	7.7
2418800.7	1910/ 5/ 9– 6	N	61 18.1	16.979	14.792	16.2	17.1	–11	61 19.9	16.968	14.463	13.7	17.0
2418992.6	1910/11/17– 0	F	61 28.7	17.122	15.272	19.1	–18.7	3	61 28.8	17.122	15.373	19.7	–18.8
2419022.2	1910/12/16–11	F	61 9.6	17.052	16.773	26.2	–23.3	–20	61 16.2	17.041	16.263	24.1	–23.2
2419184.6	1911/ 5/28– 6	N	61 16.9	16.947	16.064	23.5	21.3	11	61 18.9	16.948	16.476	25.1	21.4

Table 16

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1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2419214.1	1911/ 6/26–13	N	61 17.5	16.898	17.162	27.5	23.4	–10	61 19.4	16.900	17.081	27.2	23.4
2419376.5	1911/12/ 6– 3	F	61 5.4	17.010	16.478	25.8	–22.3	22	61 13.7	16.970	17.096	27.7	–22.5
2419406.1	1912/ 1/ 4–13	F	61 31.6	17.112	17.249	27.6	–22.8	1	61 31.6	17.112	17.248	27.6	–22.8
2419435.6	1912/ 2/ 3– 0	F	61 6.3	16.988	15.434	21.5	–17.0	–22	61 14.4	16.951	16.396	25.3	–17.2
2419598.0	1912/ 7/14–13	N	61 17.9	16.886	16.781	26.6	21.7	11	61 19.9	16.882	16.424	25.2	21.6
2419627.5	1912/ 8/12–20	N	61 18.2	16.928	14.973	18.9	14.9	–10	61 20.1	16.927	15.433	21.1	15.0
2419789.9	1913/ 1/22–16	F	61 10.0	17.030	16.008	24.1	–19.7	19	61 16.7	17.013	15.204	20.2	–19.5
2419819.5	1913/ 2/21– 2	F	61 29.2	17.105	14.204	13.4	–10.8	– 2	61 29.3	17.103	14.282	14.0	–10.8
2420011.4	1913/ 8/31–21	N	61 17.8	16.974	13.785	10.1	8.6	10	61 19.7	16.968	13.572	6.9	8.5
2420041.0	1913/ 9/30– 5	N	61 18.0	17.021	13.413	– 3.6	– 2.6	–11	61 20.1	17.031	13.379	– 0.3	– 2.4
2420203.4	1914/ 3/12– 4	F	61 11.2	17.032	13.370	3.2	– 3.7	18	61 16.8	17.021	13.390	– 2.2	– 3.4
2420232.9	1914/ 4/10–13	F	61 26.6	17.013	13.922	–10.6	7.8	– 4	61 26.8	17.014	13.826	– 9.4	7.7
2420424.9	1914/10/19– 7	N	61 22.6	17.030	14.213	–13.3	– 9.7	9	61 24.1	17.015	14.548	–15.8	– 9.8
2420454.4	1914/11/17–16	N	61 20.2	17.042	16.068	–23.7	–18.9	–12	61 22.9	17.038	15.578	–21.5	–18.8
2420616.8	1915/ 4/29–14	F	61 12.9	16.900	15.033	–18.8	14.2	17	61 17.8	16.895	15.755	–22.2	14.5
2420646.3	1915/ 5/28–22	F	61 25.7	16.914	16.833	–26.1	21.4	– 5	61 26.0	16.910	16.709	–25.7	21.4
2420838.3	1915/12/ 6–18	N	61 25.9	17.083	17.049	–26.6	–22.4	8	61 26.9	17.083	17.136	–26.8	–22.5
2420867.8	1916/ 1/ 5– 5	N	61 17.0	17.101	16.500	–24.9	–22.7	–15	61 20.8	17.080	16.901	–26.3	–22.8
2421030.2	1916/ 6/15–22	F	61 10.8	16.855	16.903	–26.3	23.3	17	61 15.6	16.865	16.719	–25.5	23.3
2421059.8	1916/ 7/15– 5	F	61 23.3	16.942	15.967	–22.2	21.6	– 5	61 23.7	16.941	16.125	–22.9	21.6
2421251.7	1917/ 1/23– 8	N	61 26.5	17.135	15.321	–18.4	–19.5	4	61 26.9	17.133	15.158	–17.4	–19.5
2421281.2	1917/ 2/21–18	N	61 12.3	17.017	13.925	– 7.2	–10.6	–17	61 17.4	17.007	14.325	–11.7	–10.8
2421443.7	1917/ 8/ 3– 5	F	61 11.9	16.881	14.789	–15.2	17.7	17	61 16.6	16.860	14.356	–11.3	17.5
2421473.2	1917/ 9/ 1–12	F	61 25.7	16.950	13.972	– 4.3	8.4	– 4	61 26.1	16.954	14.025	– 5.5	8.5
2421665.1	1918/ 3/12–20	N	61 27.2	17.037	14.017	1.2	– 3.4	2	61 27.4	17.038	14.027	1.8	– 3.3
2421694.7	1918/ 4/11– 5	N	61 8.6	16.927	14.555	12.2	8.0	–19	61 14.7	16.891	14.207	7.8	7.7
2421857.1	1918/ 9/20–13	F	61 15.3	16.909	14.059	3.2	1.3	16	61 19.6	16.895	14.263	7.1	1.0
2421886.6	1918/10/19–22	F	61 27.1	17.051	14.942	13.5	– 9.9	– 6	61 27.7	17.047	14.817	12.4	– 9.8
2422049.0	1919/ 3/31–21	N	60 57.7	16.903	14.261	7.8	4.0	24	61 7.0	16.918	14.788	12.8	4.4
2422078.6	1919/ 4/30– 6	N	61 23.5	17.003	15.466	16.5	14.4	1	61 23.6	17.005	15.507	16.8	14.5
2422108.1	1919/ 5/29–13	N	61 3.6	16.885	16.173	21.2	21.5	–20	61 10.3	16.871	15.921	19.7	21.4
2422270.5	1919/11/ 8– 0	F	61 17.9	17.049	15.582	17.1	–16.2	14	61 21.5	17.046	15.916	18.8	–16.4
2422300.0	1919/12/ 7–10	F	61 26.5	17.131	16.356	20.8	–22.5	– 7	61 27.5	17.131	16.320	20.5	–22.5
2422462.5	1920/ 5/18– 6	N	60 57.0	16.858	15.730	18.5	19.5	24	61 6.1	16.872	16.073	19.9	19.7
2422492.0	1920/ 6/16–14	N	61 22.6	16.944	16.239	20.0	23.3	1	61 22.6	16.944	16.232	20.0	23.3
2422521.5	1920/ 7/15–20	N	61 4.0	16.818	15.501	16.8	21.5	–20	61 10.7	16.827	15.902	18.8	21.6
2422683.9	1920/12/25–13	F	61 23.6	17.093	16.116	19.0	–23.4	12	61 26.1	17.077	16.005	18.3	–23.4
2422713.5	1921/ 1/23–23	F	61 26.4	17.077	15.401	14.5	–19.4	–10	61 28.0	17.071	15.605	15.8	–19.5
2422875.9	1921/ 7/ 5–14	N	60 58.5	16.787	15.741	17.9	22.8	23	61 7.3	16.777	15.451	15.7	22.7
2422905.4	1921/ 8/ 3–20	N	61 23.7	16.929	15.226	12.9	17.5	2	61 23.7	16.928	15.197	12.7	17.5
2422935.0	1921/ 9/ 2– 4	N	61 4.4	16.898	14.444	5.1	8.1	–20	61 11.1	16.900	14.729	8.8	8.5
2423097.4	1922/ 2/12– 1	F	61 24.7	17.086	14.993	10.4	–14.0	10	61 26.4	17.086	14.860	8.8	–13.9
2423126.9	1922/ 3/13–11	F	61 21.1	17.046	14.510	1.8	– 3.1	–12	61 23.5	17.036	14.587	4.1	– 3.3
2423289.3	1922/ 8/22–21	N	60 58.3	16.851	14.702	9.3	11.8	23	61 7.0	16.838	14.497	5.1	11.5
2423318.9	1922/ 9/21– 5	N	61 24.0	17.034	14.535	0.8	1.0	1	61 24.0	17.033	14.533	0.6	1.0

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2423348.4	1922/10/20–14	N	61 3.3	16.978	14.641	– 8.0	–10.2	–21	61 10.7	16.987	14.490	– 4.1	– 9.9
2423510.8	1923/ 4/ 1–13	F	61 23.7	17.043	14.543	– 2.6	4.3	8	61 24.9	17.040	14.596	– 4.1	4.4
2423540.3	1923/ 4/30–22	F	61 17.9	16.920	14.985	–10.9	14.7	–14	61 20.9	16.917	14.802	– 8.6	14.5
2423702.8	1923/10/10– 6	N	61 3.4	16.947	14.379	– 3.5	– 6.3	22	61 11.3	16.904	14.644	– 7.7	– 6.6
2423732.3	1923/11/ 8–15	N	61 28.1	17.062	15.145	–12.0	–16.4	0	61 28.1	17.062	15.141	–11.9	–16.4
2423761.8	1923/12/ 8– 2	N	61 2.9	17.001	15.738	–17.7	–22.6	–23	61 11.5	16.964	15.441	–15.4	–22.5
2423924.2	1924/ 5/18–22	F	61 23.9	16.913	15.414	–14.8	19.6	7	61 24.9	16.914	15.563	–15.7	19.7
2423953.8	1924/ 6/17– 5	F	61 16.8	16.870	16.044	–19.0	23.4	–14	61 20.0	16.854	15.905	–18.1	23.3
2424116.2	1924/11/26–17	N	61 9.2	17.000	15.451	–16.3	–21.0	20	61 15.6	16.977	15.868	–18.4	–21.1
2424145.7	1924/12/26– 4	N	61 28.4	17.122	16.287	–20.0	–23.4	– 3	61 28.5	17.120	16.273	–19.9	–23.4
2424337.7	1925/ 7/ 6– 5	F	61 21.6	16.921	16.323	–20.8	22.7	7	61 22.6	16.923	16.301	–20.7	22.7
2424367.2	1925/ 8/ 4–12	F	61 15.1	16.912	15.698	–17.9	17.3	–14	61 18.3	16.917	15.989	–19.3	17.5
2424529.6	1926/ 1/14– 7	N	61 12.4	17.091	16.247	–21.2	–21.4	17	61 17.5	17.076	16.031	–20.0	–21.3
2424559.1	1926/ 2/12–17	N	61 26.2	17.101	15.396	–16.1	–13.8	– 5	61 26.6	17.102	15.529	–16.9	–13.8
2424751.1	1926/ 8/23–13	F	61 23.8	16.945	15.115	–14.9	11.6	7	61 24.7	16.936	14.932	–13.5	11.5
2424780.6	1926/ 9/21–20	F	61 17.5	16.939	14.154	– 5.2	0.8	–13	61 20.9	16.943	14.375	– 8.4	1.0
2424943.0	1927/ 3/ 3–19	N	61 16.1	17.024	14.495	–11.3	– 7.0	15	61 20.0	17.012	14.234	– 7.9	– 6.7
2424972.6	1927/ 4/ 2– 4	N	61 24.5	16.997	13.979	0.0	4.5	– 6	61 25.3	16.989	13.996	– 1.8	4.4
2425164.5	1927/10/10–21	F	61 26.7	17.004	13.920	2.3	– 6.5	7	61 27.4	17.005	13.972	4.0	– 6.6
2425194.0	1927/11/ 9– 7	F	61 16.8	17.062	14.646	13.9	–16.6	–15	61 20.9	17.043	14.287	10.3	–16.4
2425356.5	1928/ 4/20– 5	N	61 14.4	16.959	14.011	8.3	11.4	14	61 17.7	16.976	14.345	11.8	11.6
2425386.0	1928/ 5/19–13	N	61 19.9	16.976	15.342	18.8	19.8	– 7	61 20.9	16.968	15.079	17.2	19.7
2425577.9	1928/11/27– 9	F	61 28.3	17.131	15.849	21.5	–21.1	5	61 28.6	17.131	16.021	22.3	–21.2
2425607.5	1928/12/26–20	F	61 13.8	17.070	16.933	26.3	–23.3	–18	61 19.1	17.062	16.727	25.4	–23.4
2425769.9	1929/ 6/ 7–14	N	61 13.5	16.922	16.480	25.0	22.7	13	61 16.7	16.922	16.851	26.2	22.8
2425799.4	1929/ 7/ 6–21	N	61 19.8	16.909	17.045	26.8	22.7	– 8	61 20.9	16.914	17.107	26.9	22.7
2425991.4	1930/ 1/14–22	F	61 31.3	17.109	16.855	26.0	–21.3	2	61 31.4	17.108	16.797	25.8	–21.3
2426020.9	1930/ 2/13– 9	F	61 10.6	16.993	14.857	18.0	–13.5	–20	61 17.3	16.963	15.721	22.2	–13.8
2426183.3	1930/ 7/25–21	N	61 14.9	16.877	16.242	24.5	19.7	13	61 18.0	16.868	15.717	22.2	19.6
2426212.9	1930/ 8/24– 4	N	61 20.9	16.950	14.468	15.3	11.4	– 8	61 22.0	16.951	14.764	17.2	11.5
2426375.3	1931/ 2/ 3– 0	F	61 5.1	17.005	15.322	21.2	–16.9	22	61 13.3	16.985	14.483	16.1	–16.6
2426404.8	1931/ 3/ 4–11	F	61 29.0	17.090	13.816	9.2	– 6.7	– 1	61 29.0	17.090	13.821	9.3	– 6.7
2426434.3	1931/ 4/ 2–20	F	61 3.5	16.926	13.362	– 4.6	4.8	–22	61 11.6	16.905	13.344	2.1	4.4
2426596.8	1931/ 9/12– 4	N	61 15.4	16.974	13.494	6.0	4.6	14	61 18.3	16.966	13.381	2.0	4.4
2426626.3	1931/10/11–13	N	61 21.0	17.049	13.629	– 7.8	– 6.8	– 8	61 22.3	17.056	13.503	– 5.3	– 6.6
2426788.7	1932/ 3/22–12	F	61 6.2	16.990	13.284	– 1.1	0.7	21	61 13.4	16.982	13.547	– 7.3	1.0
2426818.2	1932/ 4/20–21	F	61 26.7	17.000	14.338	–14.5	11.7	– 1	61 26.7	17.000	14.284	–14.1	11.6
2426847.8	1932/ 5/20– 5	F	61 0.8	16.796	16.011	–24.4	19.9	–23	61 9.6	16.780	15.072	–19.8	19.7
2427010.2	1932/10/29–15	N	61 20.7	17.037	14.698	–17.2	–13.5	12	61 23.0	17.018	15.200	–19.9	–13.7
2427039.7	1932/11/28– 1	N	61 23.2	17.062	16.683	–26.1	–21.2	–10	61 25.1	17.058	16.325	–24.7	–21.2
2427202.1	1933/ 5/ 9–22	F	61 7.9	16.858	15.580	–22.1	17.4	20	61 14.4	16.855	16.412	–25.3	17.6
2427231.7	1933/ 6/ 8– 5	F	61 26.2	16.906	17.195	–27.6	22.8	– 2	61 26.2	16.905	17.167	–27.5	22.8
2427261.2	1933/ 7/ 7–12	F	60 59.9	16.790	16.540	–26.2	22.6	–24	61 8.9	16.770	17.100	–27.8	22.7
2427423.6	1933/12/17– 3	N	61 24.3	17.083	17.223	–27.5	–23.3	9	61 25.8	17.081	17.177	–27.3	–23.3
2427453.1	1934/ 1/15–14	N	61 19.9	17.107	16.032	–23.3	–21.2	–13	61 22.7	17.091	16.521	–25.2	–21.3

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2427615.6	1934/ 6/27– 5	F	61 6.0	16.824	16.780	−26.4	23.3	20	61 12.5	16.833	16.294	−24.4	23.3
2427645.1	1934/ 7/26–12	F	61 24.3	16.951	15.454	−20.2	19.5	− 2	61 24.4	16.951	15.523	−20.6	19.6
2427674.6	1934/ 8/24–20	F	60 58.5	16.842	13.793	− 9.4	11.1	−24	61 7.7	16.861	14.535	−15.5	11.5
2427837.0	1935/ 2/ 3–16	N	61 24.9	17.125	14.740	−15.5	−16.7	7	61 25.7	17.122	14.524	−13.9	−16.6
2427866.6	1935/ 3/ 5– 3	N	61 15.5	17.017	13.672	− 3.2	− 6.4	−16	61 19.4	17.010	13.885	− 7.3	− 6.7
2428029.0	1935/ 8/14–13	F	61 7.6	16.868	14.274	−12.2	14.6	19	61 14.0	16.841	13.889	− 7.1	14.3
2428058.5	1935/ 9/12–20	F	61 27.1	16.973	13.796	− 0.3	4.3	− 2	61 27.1	16.974	13.800	− 0.8	4.3
2428088.0	1935/10/12– 5	F	61 0.1	16.902	14.198	11.7	− 7.0	−24	61 9.7	16.889	13.816	5.5	− 6.7
2428250.5	1936/ 3/23– 4	N	61 25.6	17.019	14.025	5.5	0.9	5	61 26.1	17.020	14.096	6.8	1.0
2428280.0	1936/ 4/21–13	N	61 12.3	16.930	14.994	16.2	11.9	−17	61 16.9	16.900	14.550	12.6	11.7
2428442.4	1936/ 9/30–21	F	61 11.6	16.907	14.124	7.5	− 3.0	19	61 17.4	16.890	14.538	11.9	− 3.3
2428471.9	1936/10/30– 6	F	61 28.7	17.071	15.410	17.4	−13.7	− 3	61 28.9	17.069	15.321	16.8	−13.7
2428663.9	1937/ 5/10–13	N	61 22.2	16.983	15.924	19.8	17.6	5	61 22.5	16.989	16.027	20.3	17.6
2428693.4	1937/ 6/ 8–21	N	61 7.9	16.901	16.415	22.6	22.9	−18	61 13.0	16.892	16.357	22.2	22.8
2428855.8	1937/11/18– 8	F	61 14.8	17.049	16.006	20.1	−19.2	17	61 19.5	17.043	16.311	21.3	−19.3
2428885.4	1937/12/17–19	F	61 28.3	17.143	16.447	21.6	−23.4	− 5	61 28.8	17.143	16.482	21.7	−23.4
2429077.3	1938/ 6/27–21	N	61 21.8	16.940	16.145	20.0	23.3	4	61 22.1	16.937	16.084	19.7	23.3
2429106.9	1938/ 7/27– 4	N	61 8.9	16.848	15.155	14.8	19.4	−17	61 13.8	16.859	15.581	17.3	19.5
2429269.3	1939/ 1/ 5–21	F	61 20.7	17.085	15.880	18.3	−22.6	14	61 24.2	17.064	15.640	16.8	−22.6
2429298.8	1939/ 2/ 4– 8	F	61 28.1	17.075	14.996	11.7	−16.5	− 8	61 29.2	17.071	15.161	13.0	−16.5
2429490.7	1939/ 8/15– 4	N	61 23.3	16.934	14.846	9.9	14.4	4	61 23.6	16.933	14.780	9.1	14.3
2429520.3	1939/ 9/13–11	N	61 9.4	16.939	14.330	1.0	4.0	−17	61 14.6	16.940	14.452	4.5	4.3
2429682.7	1940/ 2/23–10	F	61 21.7	17.062	14.648	6.7	−10.2	12	61 24.2	17.062	14.556	4.4	−10.0
2429712.2	1940/ 3/23–20	F	61 23.1	17.040	14.517	− 2.6	1.2	−10	61 24.7	17.032	14.499	− 0.6	1.0
2429904.2	1940/10/ 1–13	N	61 24.1	17.047	14.574	− 3.5	− 3.2	3	61 24.3	17.045	14.598	− 4.2	− 3.3
2429933.7	1940/10/30–22	N	61 8.4	17.016	15.009	−11.8	−14.0	−18	61 14.3	17.021	14.767	− 8.7	−13.7
2430096.1	1941/ 4/11–21	F	61 20.9	17.014	14.699	− 6.7	8.4	11	61 22.9	17.011	14.842	− 8.6	8.6
2430125.7	1941/ 5/11– 5	F	61 20.5	16.921	15.380	−14.0	17.8	−11	61 22.5	16.920	15.204	−12.5	17.7
2430288.1	1941/10/20–14	N	60 58.8	16.940	14.565	− 7.6	−10.3	25	61 8.4	16.890	14.999	−11.7	−10.7
2430317.6	1941/11/19– 0	N	61 28.5	17.075	15.544	−14.8	−19.3	2	61 28.5	17.073	15.577	−15.1	−19.3
2430347.1	1941/12/18–10	N	61 7.8	17.023	15.951	−18.4	−23.4	−20	61 14.9	16.990	15.830	−17.4	−23.4
2430509.6	1942/ 5/30– 6	F	61 21.3	16.889	15.741	−16.7	21.7	9	61 23.1	16.889	15.899	−17.6	21.7
2430539.1	1942/ 6/28–12	F	61 19.9	16.881	16.106	−18.9	23.3	−11	61 22.0	16.870	16.096	−18.8	23.3
2430701.5	1942/12/ 8– 2	N	61 5.0	16.995	15.749	−17.8	−22.6	22	61 12.8	16.966	16.048	−19.1	−22.7
2430731.0	1943/ 1/ 6–13	N	61 28.7	17.122	16.208	−19.2	−22.6	− 1	61 28.7	17.122	16.211	−19.2	−22.6
2430760.6	1943/ 2/ 5– 0	N	61 1.1	17.021	15.323	−15.4	−16.2	−24	61 10.0	16.983	15.799	−17.9	−16.5
2430923.0	1943/ 7/17–12	F	61 19.4	16.910	16.091	−19.3	21.3	11	61 21.2	16.911	15.973	−18.7	21.2
2430952.5	1943/ 8/15–20	F	61 18.5	16.941	15.305	−14.7	14.1	−11	61 20.7	16.946	15.551	−16.2	14.3
2431114.9	1944/ 1/25–15	N	61 8.3	17.072	15.849	−18.9	−19.1	20	61 14.6	17.054	15.508	−16.7	−18.9
2431144.5	1944/ 2/24– 2	N	61 26.7	17.095	14.979	−12.2	− 9.9	− 3	61 26.8	17.095	15.046	−12.7	−10.0
2431336.4	1944/ 9/ 2–20	F	61 22.1	16.952	14.733	−11.0	7.7	10	61 23.7	16.938	14.557	− 8.9	7.6
2431365.9	1944/10/ 2– 4	F	61 21.2	16.974	14.166	− 0.9	− 3.5	−11	61 23.5	16.976	14.237	− 3.6	− 3.3
2431528.4	1945/ 3/14– 4	N	61 11.9	16.993	14.223	− 7.0	− 2.7	17	61 17.0	16.982	14.088	− 2.9	− 2.4
2431557.9	1945/ 4/12–13	N	61 25.2	16.987	14.163	4.1	8.7	− 5	61 25.6	16.981	14.130	3.0	8.6
2431749.8	1945/10/21– 6	F	61 25.5	17.013	14.165	6.3	−10.6	8	61 26.7	17.013	14.313	8.4	−10.7

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2431779.4	1945/11/19–15	F	61 20.5	17.090	15.193	16.7	–19.5	–13	61 23.5	17.073	14.841	14.1	–19.4
2431941.8	1946/ 5/ 1–13	N	61 10.1	16.922	14.393	11.8	15.0	17	61 14.7	16.943	14.884	15.5	15.2
2431971.3	1946/ 5/30–21	N	61 21.1	16.972	15.840	20.7	21.8	– 5	61 21.6	16.968	15.679	19.9	21.7
2432163.3	1946/12/ 8–18	F	61 27.3	17.137	16.320	23.1	–22.7	7	61 28.1	17.135	16.512	23.8	–22.7
2432192.8	1947/ 1/ 7– 5	F	61 17.5	17.083	16.833	25.4	–22.5	–16	61 21.6	17.078	16.891	25.5	–22.5
2432355.2	1947/ 6/18–21	N	61 9.6	16.897	16.713	25.5	23.4	17	61 14.1	16.893	16.931	26.2	23.4
2432384.7	1947/ 7/18– 4	N	61 21.6	16.921	16.724	25.2	21.2	– 5	61 22.1	16.925	16.830	25.6	21.2
2432576.7	1948/ 1/26– 7	F	61 30.4	17.103	16.294	23.6	–19.0	4	61 30.8	17.100	16.151	23.0	–18.9
2432606.2	1948/ 2/24–17	F	61 14.4	16.994	14.378	14.1	– 9.7	–18	61 19.8	16.971	15.049	18.3	– 9.9
2432768.6	1948/ 8/ 5– 4	N	61 11.4	16.867	15.631	21.8	17.0	16	61 15.8	16.852	15.006	18.5	16.8
2432798.2	1948/ 9/ 3–11	N	61 23.1	16.970	14.075	11.4	7.5	– 5	61 23.5	16.971	14.224	12.8	7.6
2432990.1	1949/ 3/14–19	F	61 28.1	17.071	13.595	5.0	– 2.4	2	61 28.2	17.072	13.573	4.4	– 2.4
2433019.7	1949/ 4/13– 4	F	61 7.9	16.933	13.657	– 8.7	8.9	–20	61 14.4	16.915	13.416	– 2.9	8.6
2433182.1	1949/ 9/22–12	N	61 12.4	16.973	13.360	1.8	0.3	16	61 16.6	16.962	13.408	– 2.9	0.1
2433211.6	1949/10/21–21	N	61 23.4	17.073	14.004	–11.8	–10.8	– 6	61 24.1	17.077	13.847	–10.1	–10.7
2433374.0	1950/ 4/ 2–21	F	61 0.7	16.943	13.362	– 5.4	5.0	23	61 9.6	16.938	13.919	–12.1	5.3
2433403.6	1950/ 5/ 2– 5	F	61 26.2	16.985	14.867	–18.0	15.2	1	61 26.2	16.985	14.906	–18.2	15.2
2433433.1	1950/ 5/31–13	F	61 5.9	16.813	16.577	–26.4	21.9	–21	61 12.9	16.802	15.823	–23.2	21.8
2433595.5	1950/11/ 9–23	N	61 18.4	17.041	15.286	–20.6	–16.9	14	61 21.6	17.018	15.921	–23.4	–17.1
2433625.0	1950/12/ 9–10	N	61 25.7	17.076	17.148	–27.7	–22.8	– 8	61 26.9	17.074	16.953	–27.0	–22.7
2433787.4	1951/ 5/21– 6	F	61 2.4	16.815	16.123	–24.7	20.0	22	61 10.7	16.811	16.927	–27.4	20.2
2433817.0	1951/ 6/19–13	F	61 26.1	16.899	17.344	–28.2	23.4	0	61 26.1	16.900	17.343	–28.2	23.4
2433846.5	1951/ 7/18–19	F	61 5.4	16.823	16.131	–24.7	21.1	–20	61 12.5	16.808	16.886	–27.2	21.2
2434008.9	1951/12/28–12	N	61 22.0	17.079	17.123	–27.5	–23.3	11	61 24.3	17.076	16.879	–26.6	–23.3
2434038.5	1952/ 1/26–22	N	61 22.3	17.109	15.442	–20.9	–18.8	–10	61 24.3	17.096	15.910	–23.0	–18.9
2434200.9	1952/ 7/ 7–13	F	61 0.7	16.793	16.440	–25.6	22.6	22	61 9.1	16.799	15.657	–22.2	22.5
2434230.4	1952/ 8/ 5–20	F	61 24.7	16.959	14.895	–17.6	16.8	1	61 24.7	16.959	14.858	–17.4	16.8
2434259.9	1952/ 9/ 4– 3	F	61 4.3	16.891	13.517	– 5.6	7.2	–20	61 11.6	16.906	13.994	–11.4	7.6
2434422.4	1953/ 2/14– 1	N	61 22.6	17.111	14.198	–12.1	–13.2	9	61 24.1	17.106	13.979	– 9.7	–13.0
2434451.9	1953/ 3/15–11	N	61 18.2	17.015	13.566	1.1	– 2.2	–13	61 21.0	17.010	13.610	– 2.6	– 2.4
2434614.3	1953/ 8/24–20	F	61 2.9	16.853	13.823	– 8.7	11.0	23	61 11.1	16.821	13.581	– 2.5	10.7
2434643.8	1953/ 9/23– 4	F	61 27.9	16.993	13.765	3.9	0.1	1	61 27.9	16.992	13.769	4.0	0.1
2434673.4	1953/10/22–13	F	61 5.8	16.947	14.645	15.7	–11.1	–21	61 13.6	16.932	14.089	10.5	–10.7
2434835.8	1954/ 4/ 3–12	N	61 23.5	16.996	14.192	9.8	5.2	8	61 24.4	16.999	14.373	11.6	5.3
2434865.3	1954/ 5/ 2–20	N	61 15.5	16.931	15.532	19.8	15.4	–14	61 18.9	16.907	15.074	17.1	15.2
2435027.7	1954/10/12– 5	F	61 7.5	16.904	14.343	11.7	– 7.2	21	61 14.7	16.883	14.993	16.4	– 7.5
2435057.3	1954/11/10–15	F	61 29.7	17.087	15.953	20.8	–17.1	– 1	61 29.7	17.086	15.926	20.7	–17.1
2435086.8	1954/12/10– 1	F	61 2.0	17.037	16.593	24.5	–22.8	–23	61 11.2	16.999	16.424	23.5	–22.7
2435249.2	1955/ 5/21–21	N	61 20.3	16.962	16.359	22.4	20.2	7	61 21.1	16.971	16.486	22.9	20.2
2435278.7	1955/ 6/20– 4	N	61 11.7	16.916	16.474	23.2	23.4	–14	61 15.3	16.912	16.603	23.6	23.4
2435441.2	1955/11/29–17	F	61 11.2	17.047	16.360	22.4	–21.4	19	61 17.2	17.036	16.520	22.8	–21.6
2435470.7	1955/12/29– 4	F	61 29.4	17.150	16.319	21.5	–23.3	– 4	61 29.6	17.151	16.380	21.8	–23.3
2435662.6	1956/ 7/ 8– 5	N	61 20.3	16.935	15.877	19.3	22.5	6	61 21.1	16.929	15.723	18.4	22.5
2435692.2	1956/ 8/ 6–11	N	61 13.2	16.878	14.765	12.1	16.6	–14	61 16.7	16.890	15.130	14.8	16.8
2435854.6	1957/ 1/16– 6	F	61 17.3	17.072	15.485	16.7	–21.0	16	61 21.8	17.046	15.146	14.2	–20.8

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2435884.1	1957/ 2/14–17	F	61 29.3	17.069	14.613	8.2	–12.9	– 6	61 29.9	17.067	14.712	9.4	–13.0
2436076.1	1957/ 8/25–12	N	61 22.3	16.939	14.512	6.3	10.8	6	61 23.1	16.935	14.447	4.9	10.7
2436105.6	1957/ 9/23–19	N	61 13.9	16.976	14.344	– 3.3	– 0.2	–14	61 17.6	16.975	14.324	– 0.2	0.0
2436268.0	1958/ 3/ 5–18	F	61 18.1	17.034	14.408	2.6	– 6.0	14	61 21.7	17.034	14.409	– 0.4	– 5.8
2436297.5	1958/ 4/ 4– 4	F	61 24.6	17.031	14.663	– 6.9	5.5	– 8	61 25.5	17.025	14.587	– 5.4	5.4
2436489.5	1958/10/12–21	N	61 23.6	17.058	14.747	– 7.7	– 7.4	6	61 24.2	17.054	14.831	– 8.8	– 7.5
2436519.0	1958/11/11– 7	N	61 12.9	17.049	15.435	–15.1	–17.3	–16	61 17.4	17.051	15.177	–12.9	–17.1
2436681.4	1959/ 4/23– 5	F	61 17.5	16.981	14.963	–10.6	12.3	13	61 20.4	16.978	15.204	–12.6	12.5
2436711.0	1959/ 5/22–13	F	61 22.6	16.921	15.755	–16.5	20.3	– 8	61 23.7	16.921	15.634	–15.7	20.2
2436902.9	1959/11/30– 9	N	61 28.3	17.083	15.889	–17.0	–21.5	4	61 28.5	17.080	15.940	–17.3	–21.6
2436932.5	1959/12/29–19	N	61 12.2	17.039	15.975	–18.3	–23.2	–18	61 17.8	17.011	16.035	–18.4	–23.3
2437094.9	1960/ 6/ 9–13	F	61 18.1	16.864	15.954	–18.0	23.0	13	61 20.9	16.863	16.057	–18.4	23.0
2437124.4	1960/ 7/ 8–20	F	61 22.4	16.892	15.998	–18.0	22.4	– 9	61 23.6	16.886	16.065	–18.3	22.4
2437286.8	1960/12/18–11	N	61 0.3	16.986	15.893	–18.6	–23.4	24	61 9.7	16.950	15.993	–18.7	–23.4
2437316.4	1961/ 1/16–22	N	61 28.5	17.119	15.952	–17.6	–20.8	1	61 28.5	17.119	15.934	–17.4	–20.8
2437345.9	1961/ 2/15– 8	N	61 5.5	17.028	14.961	–11.9	–12.7	–21	61 12.9	16.997	15.399	–14.9	–13.0
2437508.3	1961/ 7/27–20	F	61 16.6	16.899	15.738	–17.1	19.1	13	61 19.4	16.899	15.532	–15.7	19.0
2437537.8	1961/ 8/26– 3	F	61 21.4	16.969	14.958	–11.0	10.5	– 8	61 22.7	16.973	15.119	–12.4	10.6
2437700.3	1962/ 2/ 5– 0	N	61 3.5	17.047	15.383	–15.9	–16.1	22	61 11.4	17.027	15.004	–12.7	–15.9
2437729.8	1962/ 3/ 6–10	N	61 26.6	17.085	14.679	– 8.0	– 5.8	0	61 26.6	17.085	14.692	– 8.2	– 5.8
2437759.3	1962/ 4/ 4–20	N	61 0.5	16.895	14.189	1.8	5.7	–23	61 9.2	16.870	14.287	– 3.2	5.4
2437921.7	1962/ 9/14– 4	F	61 19.8	16.956	14.474	– 6.8	3.6	13	61 22.4	16.939	14.362	– 4.1	3.4
2437951.3	1962/10/13–13	F	61 24.3	17.006	14.320	3.2	– 7.7	– 9	61 25.8	17.006	14.293	1.2	– 7.6
2438113.7	1963/ 3/25–12	N	61 7.0	16.955	14.106	– 2.6	1.6	20	61 13.6	16.946	14.143	1.9	2.0
2438143.2	1963/ 4/23–21	N	61 25.4	16.974	14.466	7.9	12.5	– 3	61 25.5	16.971	14.433	7.4	12.5
2438172.7	1963/ 5/23– 4	N	60 57.4	16.829	15.209	16.6	20.4	–24	61 6.9	16.789	14.686	12.2	20.2
2438335.2	1963/11/ 1–14	F	61 23.7	17.019	14.521	10.0	–14.3	11	61 25.7	17.018	14.776	12.3	–14.5
2438364.7	1963/12/ 1– 0	F	61 23.6	17.111	15.703	18.8	–21.7	–11	61 25.7	17.097	15.422	17.1	–21.6
2438527.1	1964/ 5/11–21	N	61 5.2	16.882	14.824	14.7	18.1	19	61 11.4	16.907	15.428	18.3	18.3
2438556.6	1964/ 6/10– 4	N	61 21.8	16.967	16.216	21.8	23.0	– 2	61 21.9	16.965	16.157	21.6	23.0
2438748.6	1964/12/19– 3	F	61 25.8	17.138	16.605	23.8	–23.4	8	61 27.1	17.134	16.744	24.3	–23.4
2438778.1	1965/ 1/17–14	F	61 20.7	17.090	16.513	23.6	–20.7	–14	61 23.7	17.089	16.741	24.4	–20.8
2438940.5	1965/ 6/29– 5	N	61 5.0	16.870	16.729	25.3	23.2	19	61 11.2	16.862	16.708	25.0	23.2
2438970.1	1965/ 7/28–12	N	61 22.8	16.933	16.265	22.9	19.0	– 3	61 22.9	16.936	16.334	23.2	19.0
2438999.6	1965/ 8/26–19	N	60 56.4	16.812	14.549	14.9	10.3	–25	61 6.0	16.830	15.440	19.9	10.6
2439162.0	1966/ 2/ 5–16	F	61 29.0	17.091	15.674	20.5	–15.9	6	61 29.7	17.086	15.455	19.4	–15.8
2439191.5	1966/ 3/ 7– 2	F	61 17.8	16.994	14.045	9.9	– 5.5	–16	61 21.9	16.975	14.493	13.9	– 5.8
2439354.0	1966/ 8/16–12	N	61 7.3	16.856	15.029	18.5	13.8	19	61 13.2	16.835	14.403	14.1	13.5
2439383.5	1966/ 9/14–19	N	61 24.6	16.988	13.826	7.3	3.4	– 2	61 24.7	16.989	13.873	8.0	3.4
2439575.4	1967/ 3/26– 3	F	61 26.7	17.049	13.546	0.6	1.9	5	61 27.1	17.051	13.549	– 0.6	2.0
2439605.0	1967/ 4/24–12	F	61 11.8	16.939	14.089	–12.5	12.7	–17	61 16.8	16.924	13.702	– 7.6	12.5
2439767.4	1967/10/ 3–20	N	61 9.0	16.970	13.389	– 2.4	– 3.9	19	61 14.5	16.956	13.649	– 7.7	– 4.2
2439796.9	1967/11/ 2– 6	N	61 25.3	17.093	14.514	–15.5	–14.5	– 4	61 25.6	17.095	14.381	–14.5	–14.5
2439988.9	1968/ 5/12–13	F	61 25.2	16.969	15.454	–21.0	18.2	4	61 25.4	16.968	15.609	–21.8	18.3
2440018.4	1968/ 6/10–20	F	61 10.5	16.830	16.984	–27.5	23.1	–18	61 15.8	16.824	16.504	–25.7	23.0

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2440180.8	1968/11/20– 8	N	61 15.5	17.042	15.905	–23.5	–19.7	16	61 19.8	17.014	16.583	–26.0	–19.9
2440210.4	1968/12/19–18	N	61 27.6	17.086	17.372	–28.3	–23.4	– 6	61 28.2	17.085	17.324	–28.1	–23.4
2440402.3	1969/ 6/29–20	F	61 25.4	16.892	17.249	–28.0	23.2	4	61 25.6	16.893	17.189	–27.8	23.2
2440431.8	1969/ 7/29– 3	F	61 10.3	16.856	15.607	–22.4	18.8	–18	61 15.7	16.845	16.392	–25.4	19.0
2440594.2	1970/ 1/ 7–21	N	61 19.2	17.071	16.758	–26.5	–22.3	13	61 22.3	17.066	16.297	–24.7	–22.3
2440623.8	1970/ 2/ 6– 7	N	61 24.1	17.107	14.828	–17.8	–15.7	– 8	61 25.4	17.097	15.197	–19.8	–15.8
2440815.7	1970/ 8/17– 3	F	61 24.4	16.967	14.359	–14.4	13.6	4	61 24.6	16.966	14.241	–13.4	13.5
2440845.3	1970/ 9/15–11	F	61 9.5	16.936	13.373	– 1.5	3.1	–18	61 15.1	16.947	13.600	– 6.8	3.4
2441007.7	1971/ 2/25–10	N	61 19.8	17.091	13.761	– 8.2	– 9.3	11	61 22.1	17.086	13.599	– 5.0	– 9.1
2441037.2	1971/ 3/26–19	N	61 20.4	17.012	13.624	5.4	2.2	–10	61 22.3	17.008	13.538	2.3	2.0
2441229.2	1971/10/ 4–12	F	61 28.1	17.011	13.894	8.1	– 4.2	3	61 28.2	17.008	13.953	8.9	– 4.2
2441258.7	1971/11/ 2–21	F	61 11.0	16.986	15.221	19.5	–14.8	–18	61 17.2	16.970	14.577	15.3	–14.5
2441421.1	1972/ 4/13–21	N	61 20.7	16.970	14.513	13.9	9.3	9	61 22.4	16.974	14.844	16.2	9.5
2441450.6	1972/ 5/13– 4	N	61 18.2	16.930	16.109	22.8	18.4	–11	61 20.5	16.912	15.718	21.0	18.3
2441613.1	1972/10/22–13	F	61 3.0	16.900	14.710	15.8	–11.2	24	61 11.8	16.873	15.578	20.4	–11.5
2441642.6	1972/11/20–23	F	61 30.1	17.098	16.495	23.6	–19.9	1	61 30.1	17.099	16.527	23.8	–19.9
2441672.1	1972/12/20–10	F	61 7.0	17.062	16.666	25.1	–23.4	–21	61 14.6	17.029	16.807	25.3	–23.4
2441834.5	1973/ 6/ 1– 5	N	61 17.8	16.939	16.691	24.4	22.0	9	61 19.3	16.950	16.768	24.6	22.1
2441864.1	1973/ 6/30–12	N	61 15.0	16.930	16.330	23.1	23.2	–12	61 17.4	16.929	16.585	24.0	23.2
2442026.5	1973/12/10– 2	F	61 7.1	17.040	16.557	23.9	–22.9	21	61 14.5	17.024	16.462	23.2	–23.0
2442056.0	1974/ 1/ 8–13	F	61 30.0	17.152	15.984	20.5	–22.2	– 2	61 30.0	17.153	16.022	20.7	–22.3
2442085.5	1974/ 2/ 6–23	F	61 1.7	16.970	14.423	11.7	–15.5	–24	61 11.0	16.952	15.132	16.6	–15.8
2442248.0	1974/ 7/19–12	N	61 18.3	16.930	15.471	17.8	20.9	10	61 19.9	16.920	15.216	16.1	20.8
2442277.5	1974/ 8/17–19	N	61 16.9	16.906	14.387	9.0	13.4	–12	61 19.2	16.918	14.644	11.5	13.5
2442439.9	1975/ 1/27–15	F	61 13.3	17.053	14.999	14.3	–18.5	18	61 19.0	17.021	14.626	10.7	–18.3
2442469.4	1975/ 2/26– 1	F	61 30.0	17.059	14.310	4.4	– 9.0	– 3	61 30.2	17.059	14.348	5.2	– 9.1
2442661.4	1975/ 9/ 5–19	N	61 20.7	16.943	14.270	2.4	6.8	10	61 22.2	16.937	14.256	0.3	6.7
2442690.9	1975/10/ 5– 4	N	61 17.7	17.009	14.499	– 7.6	– 4.5	–13	61 20.3	17.006	14.374	– 5.0	– 4.3
2442853.3	1976/ 3/16– 3	F	61 14.0	16.999	14.299	– 1.7	– 1.7	16	61 18.7	17.001	14.443	– 5.2	– 1.5
2442882.9	1976/ 4/14–12	F	61 25.5	17.019	14.938	–11.0	9.6	– 5	61 26.0	17.015	14.848	–10.1	9.5
2443074.8	1976/10/23– 5	N	61 22.6	17.066	15.042	–11.8	–11.4	8	61 23.7	17.061	15.204	–13.1	–11.6
2443104.3	1976/11/21–15	N	61 16.8	17.075	15.851	–17.8	–20.0	–13	61 20.2	17.076	15.648	–16.4	–19.9
2443266.8	1977/ 5/ 3–13	F	61 13.4	16.944	15.298	–14.1	15.7	16	61 17.7	16.942	15.609	–16.0	15.9
2443296.3	1977/ 6/ 1–21	F	61 24.1	16.920	16.047	–18.3	22.1	– 6	61 24.6	16.921	15.996	–18.0	22.1
2443488.2	1977/12/10–18	N	61 27.5	17.089	16.108	–18.4	–22.9	5	61 28.1	17.083	16.138	–18.5	–23.0
2443517.8	1978/ 1/ 9– 4	N	61 16.0	17.050	15.816	–17.2	–22.2	–16	61 20.4	17.027	16.013	–18.2	–22.2
2443680.2	1978/ 6/20–21	F	61 14.3	16.839	16.012	–18.4	23.4	15	61 18.3	16.834	15.998	–18.2	23.4
2443709.7	1978/ 7/20– 3	F	61 24.3	16.902	15.748	–16.4	20.7	– 5	61 24.8	16.900	15.832	–16.8	20.8
2443901.7	1979/ 1/28– 6	N	61 27.7	17.111	15.583	–15.1	–18.3	4	61 27.9	17.113	15.526	–14.7	–18.3
2443931.2	1979/ 2/26–17	N	61 9.4	17.032	14.674	– 7.9	– 8.8	–19	61 15.3	17.007	14.996	–11.1	– 9.0
2444093.6	1979/ 8/ 8– 3	F	61 13.2	16.888	15.331	–14.3	16.3	16	61 17.3	16.885	15.080	–12.0	16.2
2444123.2	1979/ 9/ 6–11	F	61 23.7	16.995	14.702	– 7.0	6.6	– 6	61 24.4	16.997	14.778	– 8.0	6.7
2444285.6	1980/ 2/16– 9	N	60 58.2	17.014	14.933	–12.4	–12.6	24	61 7.8	16.993	14.612	– 8.2	–12.2
2444315.1	1980/ 3/16–19	N	61 25.9	17.072	14.517	– 3.7	– 1.4	1	61 26.0	17.072	14.509	– 3.4	– 1.4
2444344.6	1980/ 4/15– 4	N	61 5.0	16.901	14.421	5.8	9.8	–21	61 12.0	16.882	14.338	1.6	9.5

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2444507.1	1980/ 9/24–12	F	61 17.1	16.958	14.354	– 2.5	– 0.6	15	61 20.7	16.937	14.352	0.6	– 0.9
2444536.6	1980/10/23–21	F	61 26.9	17.033	14.598	7.2	–11.7	– 7	61 27.7	17.033	14.526	5.8	–11.6
2444699.0	1981/ 4/ 4–20	N	61 1.5	16.912	14.137	1.6	5.9	23	61 9.8	16.907	14.372	6.5	6.3
2444728.5	1981/ 5/ 4– 4	N	61 25.0	16.959	14.847	11.2	15.9	1	61 25.0	16.959	14.853	11.3	15.9
2444758.1	1981/ 6/ 2–12	N	61 2.6	16.847	15.637	18.3	22.2	–22	61 10.1	16.815	15.212	15.3	22.1
2444920.5	1981/11/11–23	F	61 21.3	17.023	14.944	13.2	–17.6	13	61 24.2	17.021	15.284	15.5	–17.7
2444950.0	1981/12/11– 9	F	61 26.1	17.126	16.094	20.1	–23.0	– 9	61 27.5	17.116	15.920	19.2	–23.0
2445112.4	1982/ 5/23– 5	N	60 59.8	16.839	15.243	17.1	20.5	22	61 7.8	16.868	15.872	20.2	20.7
2445142.0	1982/ 6/21–12	N	61 21.9	16.962	16.419	22.2	23.4	0	61 21.9	16.962	16.422	22.2	23.4
2445171.5	1982/ 7/20–19	N	61 0.1	16.844	16.164	21.9	20.6	–22	61 7.8	16.860	16.426	22.7	20.8
2445333.9	1982/12/30–12	F	61 23.7	17.135	16.657	23.5	–23.2	10	61 25.7	17.128	16.679	23.5	–23.1
2445363.4	1983/ 1/28–22	F	61 23.3	17.093	16.056	21.0	–18.2	–11	61 25.5	17.094	16.344	22.2	–18.3
2445525.9	1983/ 7/10–12	N	60 59.9	16.842	16.533	24.3	22.3	22	61 7.9	16.829	16.245	22.8	22.2
2445555.4	1983/ 8/ 8–19	N	61 23.4	16.945	15.747	20.0	16.1	1	61 23.4	16.945	15.737	19.9	16.1
2445584.9	1983/ 9/ 7– 3	N	61 2.3	16.858	14.235	10.9	6.3	–22	61 10.0	16.873	14.875	15.7	6.7
2445747.3	1984/ 2/17– 1	F	61 26.9	17.075	15.093	16.9	–12.3	8	61 28.1	17.067	14.838	15.1	–12.2
2445776.9	1984/ 3/17–10	F	61 20.7	16.990	13.876	5.6	– 1.2	–13	61 23.7	16.975	14.120	9.1	– 1.4
2445939.3	1984/ 8/26–19	N	61 2.7	16.845	14.507	14.8	10.1	22	61 10.4	16.816	13.979	9.4	9.8
2445968.8	1984/ 9/25– 3	N	61 25.6	17.004	13.735	3.0	– 0.9	0	61 25.6	17.004	13.736	3.1	– 0.9
2445998.3	1984/10/24–12	N	61 1.3	16.982	13.898	– 9.8	–11.9	–22	61 9.7	16.967	13.609	– 3.6	–11.6
2446160.8	1985/ 4/ 5–12	F	61 24.7	17.023	13.660	– 3.6	6.2	6	61 25.6	17.027	13.740	– 5.5	6.3
2446190.3	1985/ 5/ 4–20	F	61 15.2	16.943	14.620	–15.8	16.1	–15	61 18.9	16.931	14.172	–12.1	16.0
2446352.7	1985/10/14– 5	N	61 5.2	16.966	13.574	– 6.5	– 8.1	20	61 12.1	16.949	14.079	–12.3	– 8.4
2446382.2	1985/11/12–14	N	61 26.5	17.109	15.111	–18.7	–17.8	– 1	61 26.6	17.110	15.046	–18.4	–17.8
2446411.8	1985/12/12– 1	N	60 58.2	17.004	16.659	–26.4	–23.1	–24	61 8.0	16.982	15.926	–23.3	–23.0
2446574.2	1986/ 5/23–21	F	61 23.5	16.950	16.025	–23.4	20.6	6	61 24.2	16.948	16.277	–24.4	20.7
2446603.7	1986/ 6/22– 4	F	61 14.5	16.846	17.175	–27.9	23.4	–15	61 18.4	16.844	16.984	–27.1	23.4
2446766.1	1986/12/ 1–17	N	61 12.1	17.041	16.456	–25.6	–21.8	18	61 17.6	17.006	17.042	–27.5	–21.9
2446795.7	1986/12/31– 3	N	61 28.8	17.092	17.312	–28.0	–23.1	– 4	61 29.1	17.091	17.352	–28.1	–23.1
2446987.6	1987/ 7/11– 4	F	61 24.1	16.885	16.926	–27.0	22.2	6	61 24.8	16.885	16.736	–26.3	22.2
2447017.2	1987/ 8/ 9–10	F	61 14.7	16.888	15.048	–19.6	15.9	–15	61 18.6	16.880	15.732	–22.7	16.1
2447179.6	1988/ 1/19– 5	N	61 15.8	17.059	16.190	–24.6	–20.5	16	61 20.0	17.051	15.556	–21.8	–20.4
2447209.1	1988/ 2/17–16	N	61 25.4	17.101	14.277	–14.2	–12.1	– 7	61 26.1	17.094	14.516	–15.9	–12.2
2447401.1	1988/ 8/27–11	F	61 23.6	16.974	13.908	–10.8	9.9	6	61 24.2	16.972	13.761	– 9.0	9.8
2447430.6	1988/ 9/25–19	F	61 14.1	16.978	13.383	2.7	– 1.2	–15	61 18.2	16.986	13.401	– 1.9	– 0.9
2447593.0	1989/ 3/ 7–18	N	61 16.4	17.065	13.468	– 4.0	– 5.1	14	61 19.6	17.061	13.425	0.0	– 4.8
2447622.5	1989/ 4/ 6– 4	N	61 22.1	17.006	13.849	9.6	6.4	– 9	61 23.2	17.004	13.684	7.3	6.3
2447814.5	1989/10/14–21	F	61 27.8	17.026	14.190	12.3	– 8.4	5	61 28.2	17.021	14.351	13.7	– 8.4
2447844.0	1989/11/13– 6	F	61 15.6	17.020	15.871	22.8	–18.0	–16	61 20.4	17.004	15.239	19.6	–17.8
2448006.4	1990/ 4/25– 4	N	61 17.4	16.941	14.964	17.8	13.1	13	61 20.0	16.946	15.460	20.4	13.3
2448036.0	1990/ 5/24–12	N	61 20.3	16.928	16.647	25.3	20.8	– 9	61 21.7	16.916	16.383	24.2	20.7
2448227.9	1990/12/ 2– 8	F	61 30.0	17.106	16.937	25.7	–21.9	3	61 30.1	17.108	16.988	25.9	–22.0
2448257.4	1990/12/31–19	F	61 11.4	17.081	16.489	24.7	–23.1	–19	61 17.6	17.054	16.903	26.0	–23.1
2448419.9	1991/ 6/12–12	N	61 14.7	16.915	16.854	25.6	23.1	12	61 17.3	16.927	16.783	25.2	23.2
2448449.4	1991/ 7/11–19	N	61 17.7	16.944	16.002	22.1	22.1	– 9	61 19.1	16.945	16.293	23.3	22.1

Table 16

1	2	3	4	5	6	7	8	9	10	11	12	13	14
			′ ″	°/DAY	°/DAY	°	°	h	′ ″	°/DAY	°/DAY	°	°
2448611.8	1991/12/21–10	F	61 2.5	17.029	16.533	24.4	–23.4	24	61 11.4	17.007	16.120	22.4	–23.4
2448641.3	1992/ 1/19–21	F	61 29.9	17.150	15.498	18.6	–20.3	1	61 30.0	17.150	15.477	18.5	–20.3
2448670.9	1992/ 2/18– 8	F	61 6.4	16.975	14.039	8.1	–11.8	–22	61 14.1	16.964	14.586	13.3	–12.2
2448833.3	1992/ 7/29–20	N	61 15.7	16.924	14.983	15.6	18.6	12	61 18.3	16.909	14.659	13.0	18.4
2448862.8	1992/ 8/28– 3	N	61 20.0	16.934	14.075	5.4	9.7	– 9	61 21.4	16.944	14.213	7.6	9.8
2449025.2	1993/ 2/ 7– 0	F	61 8.7	17.028	14.497	11.3	–15.4	20	61 15.9	16.992	14.178	6.6	–15.1
2449054.8	1993/ 3/ 8–10	F	61 30.0	17.046	14.130	0.2	– 4.8	– 2	61 30.1	17.046	14.131	0.6	– 4.8
2449084.3	1993/ 4/ 6–19	F	61 2.0	16.877	14.437	–10.6	6.7	–24	61 11.1	16.836	14.128	– 5.2	6.3
2449246.7	1993/ 9/16– 3	N	61 18.7	16.946	14.150	– 1.7	2.7	12	61 21.0	16.936	14.241	– 4.5	2.5
2449276.2	1993/10/15–12	N	61 21.0	17.037	14.796	–11.8	– 8.6	–10	61 22.7	17.034	14.614	– 9.8	– 8.5
2449438.7	1994/ 3/27–11	F	61 9.2	16.960	14.332	– 6.1	2.6	19	61 15.4	16.965	14.661	–10.0	2.9
2449468.2	1994/ 4/25–20	F	61 25.9	17.005	15.320	–14.9	13.3	– 3	61 26.0	17.003	15.258	–14.4	13.3
2449660.1	1994/11/ 3–14	N	61 21.0	17.072	15.428	–15.4	–15.1	10	61 22.8	17.066	15.659	–16.8	–15.2
2449689.7	1994/12/ 3– 0	N	61 20.1	17.095	16.178	–19.8	–22.0	–12	61 22.5	17.096	16.079	–19.2	–22.0
2449852.1	1995/ 5/14–21	F	61 8.8	16.904	15.649	–17.1	18.7	18	61 14.6	16.902	15.960	–18.6	18.9
2449881.6	1995/ 6/13– 4	F	61 25.0	16.919	16.201	–19.4	23.2	– 3	61 25.2	16.920	16.201	–19.4	23.2
2450073.6	1995/12/22– 2	N	61 26.2	17.091	16.149	–18.8	–23.4	8	61 27.3	17.082	16.112	–18.6	–23.4
2450103.1	1996/ 1/20–13	N	61 19.2	17.056	15.513	–15.4	–20.2	–14	61 22.6	17.038	15.775	–16.9	–20.3
2450265.5	1996/ 7/ 1– 4	F	61 9.9	16.814	15.900	–18.1	23.1	18	61 15.5	16.804	15.732	–16.9	23.0
2450295.0	1996/ 7/30–11	F	61 25.6	16.913	15.407	–14.0	18.4	– 3	61 25.7	16.912	15.460	–14.4	18.4
2450487.0	1997/ 2/ 7–15	N	61 26.3	17.099	15.178	–12.0	–15.2	6	61 26.8	17.102	15.091	–11.1	–15.1
2450516.5	1997/ 3/ 9– 1	N	61 12.9	17.034	14.501	– 3.7	– 4.5	–16	61 17.5	17.013	14.678	– 6.8	– 4.8
2450678.9	1997/ 8/18–11	F	61 9.2	16.877	14.932	–11.0	13.0	18	61 14.8	16.870	14.707	– 7.8	12.8
2450708.5	1997/ 9/16–19	F	61 25.4	17.018	14.564	– 2.7	2.4	– 3	61 25.6	17.019	14.583	– 3.4	2.5
2450900.4	1998/ 3/28– 3	N	61 24.7	17.055	14.498	0.7	2.9	4	61 24.9	17.055	14.506	1.4	2.9
2450930.0	1998/ 4/26–12	N	61 9.1	16.907	14.754	9.5	13.5	–18	61 14.5	16.893	14.559	6.1	13.3
2451092.4	1998/10/ 5–20	F	61 13.8	16.959	14.374	1.7	– 4.9	17	61 18.7	16.933	14.515	5.3	– 5.2
2451121.9	1998/11/ 4– 5	F	61 28.8	17.056	14.969	10.7	–15.3	– 4	61 29.2	17.056	14.896	9.9	–15.3
2451313.9	1999/ 5/15–12	N	61 24.1	16.943	15.254	14.0	18.8	3	61 24.2	16.945	15.316	14.5	18.9
2451343.4	1999/ 6/13–19	N	61 7.2	16.864	15.938	19.2	23.2	–18	61 13.0	16.840	15.676	17.5	23.2
2451505.8	1999/11/23– 7	F	61 18.5	17.025	15.370	15.7	–20.3	15	61 22.4	17.019	15.738	17.8	–20.4
2451535.3	1999/12/22–18	F	61 28.0	17.136	16.306	20.5	–23.4	– 7	61 28.8	17.129	16.237	20.2	–23.4

Table 16

Tidal Force Evaluating Significance of the Data Contained in Table 16

1. Lunar Motion in True Anomaly

It has been seen in part II, chapter 4, that solar perturbations produce a retrograde motion of the lunar perigee at times of close perigee-syzygy alignment. This motion of perigee is in a directly opposite sense to that of the of the Moon will add vectorially to the daily motion of the Moon in true anomaly tabulated in columns 5 and 11 of table 16 is measured with respect to perigee, any motion of this orbital position in an opposite direction to that of the Moon will add vectorially to the daily motion of the Moon relative to perigee.

The result will be a value of the daily rate of lunar motion which is in excess of the motion in celestial longitude obtained by taking daily differences in *The American Ephemeris and Nautical Almanac*. This accounts for angular velocities in columns 5 and 11 which are consistently 1.3° to 1.7° greater than even the maximum daily velocity of the Moon (15.4°) at perigee-syzygy, measured in celestial longitude and with respect to the vernal equinox. The difference is due to the relative angular motion of perigee. (See ch. 4—"The Special Motion of Perigee Close to the Position of Perigee-Syzygy Alignment.")

A further advantage of these two columns of the table is that they indicate the velocity of the Moon in its orbit rather than as geometrically projected along either the celestial equator (in right ascension) or the ecliptic (in celestial longitude).

Summarily presented, the use in columns 5 and 11 of the Moon's rate of angular motion in true anomaly at the instants of syzygy and perigee serves as an excellent single-parameter indicator of the combined tide-raising forces of the Moon and Sun at these times for the following reasons:

a. REPRESENTATION OF THE SOLAR INFLUENCE

It has been shown previously that variable solar forces determined by the Moon's changing distance from the Sun and relative angle of alignment therewith are responsible for perturbations in the lunar orbit and an oscillatory motion of perigee. It is these same solar forces which combine with lunar gravitational forces at times of perigee-syzygy to produce amplified tides on Earth. Thus, any variance in the solar force upon the lunar orbit caused by the changing distance of the Earth from the Sun in consequence of the Earth's own elliptical orbit will be reflected in the rate of motion of the lunar perigee. As noted in the introductory section above, any such motion of perigee will, in turn, affect the velocity of the Moon with respect to this selected reference point.

A distinct advantage derives from the later use of this particular velocity component as one astronomical constituent of a coefficient of tidal flooding potential. This is because any diminished distance between Moon and Sun appears directly as a small additive function to the rate of lunar motion in true anomaly. The circumstance may be confirmed by calculating the interval (in days) separating each of the tabulated instances of perigee-syzygy from the nearest date of perihelion (solar perigee). This will involve a maximum of 182.5 days' separation from perihelion to the next succeeding or following aphelion, beyond which the time interval to perihelion again decreases.

It is obvious from such an analysis that those values of the lunar motion in true anomaly which are seemingly too large in comparison with the corresponding parallax are the result of a particular closeness in time to solar perigee. Similarly, velocity values which are apparently too low to accord with the indicated parallax contain the effects of a relatively large separation from solar perigee. The principal factor establishing the value of the lunar parallax is the separation-interval between perigee and syzygy as described below—added to whose effects the variation of the Moon's distance from the Sun acts as a modulating influence.

b. REPRESENTATION OF THE SEPARATION-INTERVAL

A second practical advantage in the use of velocity in true anomaly is that it possesses a definite relationship to the separation in time between perigee and syzygy. In this respect it takes into account increasing values of the parallax (and a corresponding lessening of the perigee distance) as a function of closer proximity in the perigee-syzygy alignment. Exceptions from a nearly one-to-one correspondence between the velocity in true anomaly and the lunar parallax are imposed by any circumstance of a particularly close approach of perigee-syzygy to solar perigee as previously noted. However, these and other modifying factors are applied in strictly incremental or decremental fashion. The highest values of the rate of lunar motion in true anomaly are most commonly found at close perigee-syzygy alignments (1–2 hours' separation) occurring within at least a few months of perihelion.

c. INDICATION OF INCREASED LUNAR VELOCITY IN ORBIT IN ACCORDANCE WITH KEPLER'S THIRD LAW

That part of the Moon's indicated angular velocity in true anomaly which remains after the retrograde velocity of perigee is subtracted, constitutes by far the greater portion of the resultant of the vectorially combined velocities tabulated in columns 5 and 11. Since the velocity represented is the true one occurring in the plane of the lunar orbit, it is not affected by the Moon's excursions in declination as are the values in columns 6 and 12.

However, the velocity in true anomaly is directly influenced by the relative proximity of perigee to the Earth in any one lunation as the Moon revolves in its elliptical orbit. Any diminished distance of the Moon from the Earth becomes a direct function of (1) the increase in orbital eccentricity at the time of perigee-syzygy alignment, as determined by (2) the increased magnitude of the perturbational forces acting at this time, which are, in turn, dependent upon (3) the closeness of the perigee-syzygy alignment and the commensurability of the lunar periodic relationships making possible these alignments. The greater orbital velocities of the Moon at such times of decreased distance from the Earth, as demanded by Kepler's Third Law—with the accounted-for exceptions previously noted—are quite logically found among the values given in columns 5 and 11.

The value of the lunar parallax, on the other hand, is implicitly related (through the chain of events above enumerated) to the perigee-syzygy separation-interval of column 9, and possesses a close degree of correlation therewith. It is important to note that, although a one-to-one relationship between increased parallax and increased velocity in true anomaly does not exist, the variations causing this lack of direct correlation have, for the most part, been introduced by the changing conditions of solar gravitational force described in paragraph 1. Thus, for example, where a very high value of lunar parallax exists and is not matched by a correspondingly high value of lunar velocity in true anomaly, this lunar velocity has almost inevitably been reduced by the occurrence of the perigee-syzygy alignment at a time considerably removed from solar perigee—perhaps even at solar apogee. In considering the enhanced tide-raising action produced by the combined gravitational forces of the Moon and Sun at perigee-syzygy, it is necessary to have the effects of both of these forces represented in any index-quantifier proposed for potential tidal flooding.

2. Representation of Increased Lunisolar Tidal Forces in Those Cases Where the Sun Is Simultaneously in the Moon's Orbital Plane

It is further possible by means of table 16 to include an evaluation of the additional small component of lunar motion in true anomaly provided by the presence of the Sun in the Moon's orbital plane, should the Moon be crossing the ecliptic at the same time it reaches perigee-syzygy.

This situation can be at least approximately assessed by taking the algebraic difference between the declinations of the Moon and Sun at the time of syzygy as tabulated in columns 7 and 8. Should this difference be less than 0.2°, a solar or lunar eclipse is very apt to have accompanied this syzygy alignment, although—as precisely determined—the exact position of the Moon's nodes along the ecliptic must be considered. (See footnote on p. 7.) At the same time, the gravitational force on the Earth is enhanced by the combination of the solar and lunar forces along two nearly superimposed axes.

It is obvious from an analysis of columns 7–8 and 13–14 that, in those cases in which the differences between the declinations of the Moon and Sun are very small (with due consideration to algebraic sign) the lunar velocities given in columns 5 and 11 are at least slightly above the average value which would be indicated by the corresponding parallax. This increment in velocity represents the combined gravitational influence of the Moon and Sun exerted simultaneously in dual, orthogonally intersecting planes.

In addition to the increased solar force on the Moon at perigee-syzygy associated with solar perigee as described in paragraph 1a, therefore, an additional component of solar force is provided by the Sun being in or near the Moon's orbital plane. Such a coplanar alignment in celestial latitude (or declination) is evidenced by a slight increase in lunar velocity with respect to a proportionately accelerated, but oppositely directed motion of perigee at this time.

3. Representation of Increased Lunar Motion in Right Ascension at High Values of Lunar Declination

Columns 6 and 12 represent the orbital motion of the Moon as projected from the plane of its orbit on to the celestial equator. Since the latter plane is that in which or parallel to which the apparent diurnal motions of the celestial bodies occur as the result of the Earth's rotation, these columns are especially advantageous in determining the relative catch-up motion required for the rotating Earth to bring the Moon to transit of the meridian.

In chapter 8, this joint indication of necessary catch-up times and lengthening of the tidal day at times of perigee-syzygy will be incorporated as a secondary astronomical term in establishing a coefficient of potential tidal flooding.

The apparent motion of the Moon in right ascension, as earlier explained, bears a direct relationship to its declination at the moment. It is obvious from a comparison of columns 6 and 12 with columns 7 and 13 that such increased velocities in right ascension occur when the Moon is near its highest declination angles.

In summary, it is seen that all of the principal factors which make for an increased gravitational attraction of the Moon and Sun on the Earth's tidal waters at times of perigee-syzygy are represented by the corresponding pairs of values tabulated in columns 4, 10; 5, 11; 6, 12; 7, 13; 8, 14; and in column 9. The single terms contained in columns 5 and 11 likewise very effectively consolidate the conditions expressed by seven of the remaining terms and incorporate the Sun's gravitational influence as well.

A separate advantage exists in the use of the data given in columns 6 and 12 as a measure of the daily angular velocity of the Moon in a plane parallel to the celestial equator. The role of this term in establishing the catch-up motion necessary for the rotating Earth to bring the Moon to the local meridian of a place will be extensively discussed in chapter 6.

Chapter 6.

Conditions Extending the Duration of Augmented Tide-Raising Forces at the Times of Perigee-Syzygy

As had been seen in the preceding chapters, by far the greatest portion of the increase in amplitude (or range) of the tides accompanying situations of perigee-syzygy is the result of a vector combination of the augmented gravitational forces of the Moon and Sun—together with a reduction in the distance of the Moon from the Earth at such times. These gravitational reinforcements and enhancements are responsible for a corresponding amplification of the tide-raising potential, and—when a coexisting strong onshore wind prevails—add proportionately to the possibility for tidal flooding.

Yet there is another category of dynamic influences contributing to the increased rise of the tides associated with the near-coincidence of perigee and syzygy. On such occasions, the effectiveness of the tide-raising forces discussed in chapter 5 is further enhanced by an increase in the total period of time during which such forces act at magnitudes close to their maximum values. One of the factors conducive to such force-protracting influences is an extra "catch-up" motion required of any position on the Earth's surface in accomplishing a meridian transit of the Moon (and a very nearly coincident transit of the Sun) at the time of perigee-syzygy.

The General Principles of "Stern Chase" Motion

The most important dynamic element involved in this necessity for catch-up motion is a temporary acceleration in the orbital angular velocity of the Moon at perigee, which the rotating Earth must overcome for any surface point to achieve a lunar transit. Secondly, the declinations of both the Moon and the Sun just prior to, and while passing through the position of perigee-syzygy, play a contributing role in the amount of catch-up motion required. The position of maximum declination determines the time at which the apparent motion of either of these two bodies will be predominantly in the coordinate of right ascension, and hence within a plane parallel to the celestial equator. Their apparent motions in the direction of the Earth's rotation will then be the greatest, and the necessary catch-up motion by the rotating Earth to achieve a meridian transit of these bodies will reach a maximum.

Factors Increasing the Length of the Tidal Day

Each of the above-mentioned influences acts to increase the length of the *tidal day* (and, in similar fashion, that of the *lunar day*). These two slightly different chronological concepts are distinguished, in terms of their immediate application, later in this same chapter. The circumstances yielding a contribution to tidal amplification as the result of such catch-up motions at perigee-syzygy are outlined below and are amplified in subsequent sections.

1. Lunar Parallactic Inequality

The force-prolonging influence associated with this phenomenon originates from the necessity for the rotating Earth to catch up with a temporarily induced, more rapid motion of the Moon, revolving in its orbit around the Earth in the same relative direction as the Earth rotates on its axis. This catch-up motion is imposed at perigee-syzygy by an increase in the Moon's orbital velocity produced, in response to Kepler's third law, by a closer proximity to the Earth. The greater proximity of the Moon to the Earth is in consequence of: (a) the elliptical shape of the lunar orbit; (b) the location of the Moon at the lower apse of the orbit at time of perigee-syzygy; and (c) a further incremental increase in parallax at this time resulting from a corresponding increase in eccentricity of the lunar orbit.

It must be clearly emphasized that this catch-up motion, taken by itself, is of a magnitude having only a comparatively small influence upon the production of extreme perigean spring tides. Its principal significance lies in providing support to other tide-raising and tide-prolonging factors. The maximum catch-up effect extending the length of the tidal day because of the considerably greater lunar velocity in orbit at perigee-syzygy compared with apogee-syzygy (see table 10) is some 10–13 minutes, depending upon declinational circumstances.

The effect of this extended duration of the tidal day is added to by another influence resulting from dynamic conditions at the time of perigee-syzygy. As mentioned on page 179, section 3, a perturbed rotation of the position of perigee itself occurs in a retrograde sense as the Moon's apparent motion brings it simultaneously to syzygy and perigee. Again, only when combined with other tide-raising influences does this small perigee motion achieve a quantitatively significant meaning. However, for the sake of documentary completeness, the particular contribution of this perturbed motion of perigee in the immediate vicinity of perigee-syzygy will be described later in this chapter.

2. Declination Effects

It has been shown that, in direct contrast to the reflected (diurnal) motion caused by the Earth's rotation, the greatest actual positional change of the Moon or the Sun in right ascension (resulting from their respective monthly and apparent annual motions) occurs when either of the two bodies is at its maximum declination. Under the same conditions, the angular *velocities* of these celestial objects also attain their maximum components in right ascension (α), with little or no constituent velocity in declination (δ).

Both the Moon and the Sun in their corresponding real and apparent revolutions on the celestial sphere move eastward toward increasing values of α. The Earth also rotates in this same direction. Accordingly, any increase in the motion of the Sun or Moon will necessitate an additional catch-up motion by the rotating Earth to secure the meridian transit of these two bodies. The resulting possibilities for the occurrence of such prolonged catch-up motions are:

(a) Twice each tropical month, the Moon reaches positions of maximum declination, alternatively north and south of the celestial equator. In each of these two positions, the Moon's orbital path reaches a minimum of declination change, and then recurves equatorward. In these same two positions, the Moon's apparent angular velocity in right ascension also acquires its maximum value.

In matching to this increased velocity, the requirement exists for a longer period of catch-up motion in order for the rotating Earth to achieve nearly coincident meridian transits of the Moon and Sun at perigee-syzygy. The Earth must complete an additional portion of a full axial rotation to accomplish each such meridian passage. Because of the increased motion in right ascension evidenced as the Moon approaches either position of maximum declination, the greatest influence of this particular modification of the catch-up interval in extending the tidal day occurs at these two times.

(b) Twice each tropical year, at the summer and winter solstices, respectively, the Sun similarly moves to declinations farthest north and south of the celestial equator. At these times, the apparent solar motion in right ascension also reaches its greatest values (although variable within the draconitic or nodical cycle).

Since syzygy involves the common alignment of the Moon with the Earth and Sun, the attainment of this syzygy position is dependent upon the Moon catching up with any such accelerated motion of the Sun over an appropriate interval of time. Likewise, to feel the additional tidal effect of the alignment of those two bodies at perigee-syzygy, the Earth must rotate a little farther to catch up with the nearly common Sun-Moon axis and achieve a meridian transit thereof. The tidal day is engthened proportionately.

3. The Counterproductive Influences of Solar Perigee (Perihelion)

The effect of a combination of a large (coplanar) declination and proximity to perihelion in increasing the value of the lunar parallax and hence the tidal forces acting, has been clearly demonstrated in the discussion accompanying table 13 of chapter 5. The influences of the comparatively close agreement in time between the occurrence of perihelion and the winter solstice as these phenomena individually augment (a) the tide-raising forces and (b) the length of the tidal day also have been described. Finally, as will be noted in a subsequent section, the proximity of the Sun to the Earth and Moon at time of perihelion adds to the solar gravitational force which, at perigee-syzygy, swings the line of apsides through a retrograde angle and, in so doing, slightly extends the duration of the tidal maximum attained.

By contrast, arising out of an astronomical quantity known as the *annual equation,*[1] a counterproductive factor exists which causes a *decrease* in the orbital velocity of the Moon at times of perihelion and hence acts as a direct modifying influence upon the catch-up motion described in (1) above. The apparent motion of the Moon in either celestial longitude or right ascension is correspondingly reduced. Should perigee and perihelion occur together, this factor subtracts from the tendency for an increase in the length of the tidal day at perigee-syzygy.

The motions of the Sun or the Moon *in declination* are not strongly affected, either by the Sun's passage through perihelion, or by the Moon's passage through perigee, respectively. However, if perigee-syzygy and perihelion nearly coincide in time, together with a coplanar alignment of the Sun and Moon in declination (see table 13), the influence of the combined action both in increased tide-raising force and extension of the duration of this force by necessary catch-up motions usually is quite noticeable in terms of the heightened tides produced.

As an additional relevant circumstance, the dates of perihelion (usually about January 2–4) and the winter solstice (averaging about December 23) occur quite close to each other. This circumstance, which unites two influences (the one due to perihelion, yielding an increased gravitational force, the other a maximum solar declination, resulting in an increased apparent motion of the Sun and a lengthened tidal day) acts to offset 3 (the slowing action in the Moon's orbital motion produced near perihelion). The net influence of such a combination thus still serves to reinforce the augmented tide induced by a perigee-syzygy alignment at this time.

4. Summary

Significantly, in each of the cases described above, the lengthened periods of lunisolar tidal force action occur at times during which the magnitudes of these forces also have been increased—partially by the reduced distances of the Moon and Sun from the Earth, and partially by their combined, reinforcing, gravitational attractions.

Each extended tidal day in which enhanced tide-raising forces are active contains (with some few exceptions) the occurrence of a higher high water. The resulting quantitative effects thereon are illustrated by graphs for various tide stations in figs. 153–163 of chapter 8. It is noteworthy that, compared with the tide-heightening effects produced by force amplification, this extended period of force action can provide only a supplementary and considerably less sizable role in the production of augmented high waters.

However, such a small but observationally detectable lengthening of the tidal day accompanies each near-coincidence between perigee and syzygy, as will be shown in succeeding sections of the present chapter. The incremental amplification of the tides which results when these particular catch-up induced extensions of the tidal day (as opposed to extensions which occur also at each quadrature, for example) coincide with periods of increased tidal force action will be discussed both in this chapter and in chapter 8. It should be observed that a similar bracketing of the times of low water by such a prolongation of the period of increased gravitational force application does not in any way interfere with, nor compensate for, the increased rise in water level at high tides.

Reintroduction of the Concepts of the Lunar and Tidal Day

Various introductory concepts relative to the lunar and tidal days, citing the precise differences between them, have been discussed in part II, chapter 2, and it will not be necessary to repeat these. At this juncture, it is important to point out certain practical variations in the length of the *lunar day* which result from changing catch-up motions of the rotating Earth. These are responsible for similar variations in the length of the *tidal day,* and in this respect introduce new complications in the immediate problem at hand.

The following brief review will, therefore, cover appropriate aspects of the lunar day which relate to: (1) its origin in the respective revolutionary and rotational motions of the Moon and Earth; (2) fluctuations in the length of this day resulting from the necessity for the Earth's rotational catch-up motion; and (3) the production of corresponding variations in the length of the tidal day.

Specific astronomical factors which alter the length of the lunar day, such as changes in the *daily lunar retardation* time, also will come under consideration. In the associated quantitative analysis, an alternate method for determining the length of the mean lunar day, using a different approach but realizing the same results as those in chapter 2, provides an independent confirmation thereof.

Fluctuations in the Lunar and Tidal Days

The lunar day is longer than the conventional mean solar day of 24^h0^m because the Moon revolves around the Earth in the same direction as the Earth rotates on its axis. If the period of time between two successive meridian transits of the Moon is defined as the *lunar day* in the same way that the *solar day* represents the period between two successive meridian transits of the Sun, a very obvious connection exists between these two periods of time as a function of the relative motions of the two bodies.

1. Derivation of the Length of the Mean Lunar Day

The Moon orbits once around the Earth from position of new moon to new moon again (i.e., from one conjunction of the Moon and Sun to the next) in a synodic month of 29.530589 mean solar days. As seen from the Earth, during this period the Moon describes an average 389° circuit of the celestial sphere (i.e., its sidereal revolution, plus a catch-up motion on the apparent motion of the mean sun in the same interval). The Earth rotates through approximately 361° on its axis (allowing for the Sun's own apparent mean daily motion) in 24 mean solar hours, to complete two successive meridian transits of the mean sun and accomplish the mean solar day. Both of these cases involve catch-up intervals caused by the orbital and rotational motions of the Earth in the same direction.

Similarly, the Moon revolves in its orbit in the same direction that the Earth rotates on its axis. The rotating Earth must, therefore, in a like fashion catch up with the position of the Moon in order for the Moon to transit the local meridian of a place and complete a lunar day. In so doing, the Earth must fulfill an additional portion of its rotation equal to the angular distance through which the Moon has moved ahead of the meridian of the place during that same day (i.e., a distance equal to 1/29.530589th part of the Moon's monthly revolution).

In a period of 29.530589 days, the Earth falls back, in equivalence of time, one full rotation with respect to the Sun. The corresponding period of time for the Moon to complete one synodic revolution, expressed in lunar days, is a full day less, and 29.530589 mean solar days exactly equals 28.530589 lunar days. The mean lunar day is, accordingly, established in relation to the mean solar day by the proportion:

$$\begin{aligned} 1 \text{ lunar day} &= 29.530589/28.530589 \\ &= 1.035050 \text{ mean solar days} \end{aligned}$$

Or, expressed in terms of hours and minutes

$$\begin{aligned} 1 \text{ mean lunar day} &= 24^{h}0^{m} \times 1.035050 \\ &= 24.841200^{h} = 24^{h}50.472^{m} \end{aligned}$$

2. Variations in the Lunar Day

Therefore the lunar day is, on the average, 50.472^{m} longer than the mean solar day, but—of special significance in relation to tides—the actual instantaneous value may range from approximately 38^{m} to 66^{m}.[a] The figure 50.472^{m}, representing the average difference between the lengths of the lunar and solar day, may also be thought of as representing the increment in time which, added to 24 mean solar hours, gives the period of elapsed time between two successive transits of the *mean moon* across the meridian of the place. It is thus equivalent to the delay in transit times caused by the eastward orbital motion of the Moon, and is known as the *mean daily lunar retardation*. Because of the dependence of this factor upon the actual observed transit times of the Moon, and the possible large variations in the rate of motion of the Moon in right ascension, the instantaneous value thereof ranges widely between the limits noted.

The differences between the instantaneous and mean values of the daily lunar retardation are due largely to the elliptical shape of the Moon's orbit (including its changing eccentricity, caused by long-term perturbations—as well as the effects of *variation* and *evection* described at length in chapter 4). To these dynamic effects are added the changing inclination of the Moon's orbit with respect to the celestial equator at different latitudes on the Earth (which, as seen on pp. 193–196, further modifies the continuously changing declination angle of the Moon associated with its motion in orbit). In addition to these astronomically produced, worldwide influences, the local meridian transit of the Moon is affected both by the latitude of the observer and the difference in longitude of the place of observation from Greenwich, England—for the transit of whose prime meridian the various astronomical data appearing in *The American Ephemeris and Nautical Almanac* are published.

A combination of these astronomical and geographic influences results in a continuously changing daily lunar retardation which, if plotted against the time, follows a pattern closely analogous to that of the Sun's annual equation of time. However, other factors resulting from the geographic location of the observer on the surface of the Earth—including the local azimuth and altitude (or zenith distance) of the Moon, its topocentric distance from the surface of the Earth (affected both by geographic latitude and, to a limited extent, by the elevation of the observer above mean sea level)—additionally influence the lunar retardation and the times of moonrise and moonset on the local horizon.

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[a] Most of this maximum increase in the length of the lunar day is due to the increased velocity of the Moon at perigee-syzygy and the required catch-up motion by the rotating Earth. Thus $15.4^{\circ/d} \div 360^{\circ/d} = 0.0428^{d} \times 1{,}440^{m/d} = 61.6^{m}$. The remaining difference is principally due to declinational effects.

3. Variations in the Tidal Day

It is now desirable to consider the effects of these variations in the length of the *lunar day* and in the amount of the daily lunar retardation as they influence the length of the *tidal day* and the maximum daily height of the tides. The tides are implicitly related to the changing positions of the Moon—especially its distance, meridian altitude, and time of meridian transit. Additional and often larger variations are introduced in the corresponding daily retardation of high and low waters by hydrographic, hydrological, climatological, meteorological, and other factors. The hydrographic influences pertain principally to the depth of the water and the local lunitidal interval at the place; further local variations in the times of arrival of the tides are introduced by the lunar *phase age* and *parallax age* for that locality. (See the correspondingly titled section at the end the present chapter.)

Thus, all factors considered, the length of the *mean lunar day* (the period between two consecutive upper transits of the mean moon across the local meridian of a place) and the *mean tidal day* (the average period of time between two successive higher high waters or other tides of the same phase at the same location) are not synonymous, although closely related.

The deviation of the instantaneous value of the tidal day from the average value of $24^h50.47^m$—which is generally accepted for the length of the mean lunar day—has a particular significance in terms of any near-coincidence between perigee and syzygy. In this regard, a very useful quantitative indicator for tidal flooding potential results if the time intervals between successive higher high waters are systematically tabulated. The special importance and manner of application of such a series of daily tidal retardation times, computed from the tide tables, become appropriate topics for discussion in chapter 8. However, with due consideration to the complex nature of the various forces involved, before the distinctive patterns revealed by these differences at times of perigee-syzygy are analyzed in terms of their possible value for prediction in connection with tidal flooding, the respective astronomical causes for the consistency of these patterns will be examined.

Causes of Systematic Variations in the Length of the Tidal Day

Two principal dynamic causes have previously been given for the difference between the lengths of the tidal day and the mean solar day. These are (1) the Moon's varying velocity of revolution in orbit, and (2) the rotational velocity of the Earth upon its axis. The Earth's rotational velocity is constant over centuries of time within very narrow limits. It is obvious, therefore, that any purely physical variations in the length of the tidal day—and hence in the values of the daily tidal retardations—derived from tide tables must be due, in one way or another, to factors relating to the changing positions, motions, and velocities of the Moon, together with its phase relationships with respect to the Sun.

However, other causes for such observed variations exist which are individually attributable to astronomical, geographical, and computational factors.

a. Astronomical causes for changes in the Moon's orbital velocity are associated with: (1) the elliptical shape of the lunar orbit which results in continually changing distances of the Moon from the Earth, and correspondingly altered lunar orbital velocities; and (2) both periodic and irregular disturbing influences (perturbations) of an external nature, which likewise act to alter the instantaneous positions and velocities of the Moon. These various astronomically induced tide-raising effects are felt worldwide over the Earth's surface.

b. At any one position on the Earth, further sensible changes in the times of local meridian transits, and in the lengths of the tidal day and the daily lunar retardation, are introduced by the particular geographic longitude and latitude of the place, the Greenwich hour angle of the Moon, and its azimuth and altitude (or zenith distance) at the time of upper transit.

The use of arbitrary corrections for the times of high and low water at a subordinate tide station, based upon values determined empirically for certain standard stations, is another approximation which may be responsible for computational inexactness in the length of the tidal day.

c. Finally, other less marked variations are introduced as a function of averaged, or approximate rather than actual, lunar positions. In the computational assumption thereof, these can affect both the calculated length of the tidal day and the value determined for the daily tidal retardation. Significantly, in this regard, the corrections for certain velocity-related parameters are the result of adjustments to the average (mean), rather than real motions of the Moon.

Such approximations are subjective ones generally utilized as a matter of calculating convenience which, in this arbitrary computational procedure: (1) incorrectly represent the true positions and velocities of the Moon (such as by the customary representation of the lunar motion in celestial longitude in lieu of its own orbital plane or, in dealing with catch-up effects, in the plane

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of the Earth's Equator); (2) make use of averaged (mean) lunar positions and motions rather than instantaneous, actual (true) positions. This results in a need for a successively adjusted series of computational corrections to accommodate the approximations involved.

The Role of the Increased Tidal Day Viewed in Perspective

According to the thesis advanced in this study, the potential for tidal flooding is dependent variously upon: (1) the presence of increased gravitational forces; (2) a greater length of time for these increased gravitational forces to act; (3) a very rapidly accelerating growth rate as represented by the curves indicating the rate of tide rise; and (4) a more readily achievable velocity coupling between the comparatively more rapidly moving surface current produced by perigean spring tides and any accompanying wind movement over the sea. The first premise was adequately demonstrated in chapter 5; the second will receive special attention in the present chapter; and the third and fourth will be illustrated by examples in chapters 7–8. The ensuing sections of this present chapter will be devoted to an explanation of the conditions under which the total duration of the tidal day varies, and the nature of the factors which act to modify its length, together with a quantitative interpretation of these variations.

At the outset, it should be duly emphasized that various astronomical factors may interact to alter the length of the lunar day. Thus, apparently contradicting what has been said concerning the special significance of the syzygies, it must be clearly recognized that both the lunar and tidal days may, in fact, attain a maximum length around either of the quadrature phases of the Moon, due primarily to declination effects (see figs. 44–45).

However, with due regard to accompanying gravitational reinforcements, the lengthened tidal day is most effective in producing unusually high waters when the Moon is in a position of closest monthly approach to the Earth and the tide-raising forces have been increased both by this diminished distance and by the simultaneous longitudinal alignment between the gravitational forces of the Moon and Sun at new moon or full moon. It is the invariable increase in the lengths of both the lunar and tidal days (not necessarily to a maximum) coincidentally or nearly so with the augmented gravitational forces resulting from the concurrence of perigee and syzygy that adds its influence to the production of tides of increased daily amplitude and range.

Effect of Increased Lunar Orbital Velocity Upon the Length of the Tidal Day

Several cogent points of distinction are now necessary. At the time of perigee-syzygy, because of the increased gravitational force caused by the Moon's closer proximity to the Earth, the lunar velocity in orbit is increased. The Sun's alignment with the Moon at either position of syzygy of itself also has a slight velocity-increasing effect on the Moon, induced by the lunar variation. By contrast, a small, net counterproductive influence in slowing the Moon's orbital velocity is provided when the Earth reaches its annual perihelion position, about January 2–4. The Sun's retardation of the Moon's orbital velocity is, in fact, quantitatively dwarfed by the far greater average value of the Moon's angular velocity in orbit, and especially by the increase in velocity produced at perigee-syzygy. Thus the occurrence of perigee-syzygy results at all times in a very considerable net gain in lunar velocity.

However, the above synopsis points amply to the fact that any catch-up requirements applied to the Moon's orbital motions must be separately evaluated in terms of their relationship to ordinary syzygy, or to perigee-syzygy—the influences which lengthen the tidal day working generally in the same direction, but in different degrees, at these two times. (Cf., tables 21–22.)

The greatest increase in the Moon's orbital motion is from about 11.8°/day at apogee- (exogee-) syzygy to about 15.4°/day at perigee- (proxigee-) syzygy, a difference of 3.6°/day. This stated maximum value also indicates an angular velocity at proxigee-syzygy which is 2.2°/day greater than the mean lunar orbital velocity (sidereal) of 13.2°/day. It is the total gain in velocity of 3.6°/day, acquired steadily between exogee-syzygy and proxigee-syzygy, with which the rotating Earth must catch up during the 24-hour period bracketing proxigee-syzygy. It should be reiterated that the effect of the daily catch-up motion by the rotating Earth resulting from the more rapid orbital motion of the Moon at perigee-syzygy compared with that at apogee-syzygy is small in units of time. The maximum lengthening of the tidal day due to this cause alone amounts to $\frac{3.6^\circ/^d}{360^\circ/^d} \times 1^d = 0.01 \times 24^h/^d = 0.24^h$, or about 14.4 minutes. However, this effect is additive to, and in support of, other influences. Further, and of greater importance to the present discussion, the force-protracting influence of a perigee-syxygy alignment upon the tides is greater than that which exists at ordinary spring tides, as described in chapter 7.

Quantitative Evaluation of Changing Periods in the Moon's Monthly Revolution

A quantitative evaluation of the influence of perigee-syzygy alignments on the lengths of successive synodic and anomalistic months during a 209 synodic-month period from January 1959 through December 1975 is provided in table 17. The discussion to follow will reveal a maximum lengthening of the synodic month above its mean value amounting to +0.2992 day, and a maximum lengthening of the anomalistic month above its own mean by 1.02 days, both at a time of perigee-syzygy. A corresponding lengthening of the individual *lunar* and *tidal days* contained within these months readily can be shown to be associated with perigee-syzygy.

As the result of a frequent contiguous usage of these words in the text, several apparently related, but actually quite different concepts involving the length of the *lunar day* and the length of the *synodic month* should be clarified at this point. The lunar day is measured by the time between consecutive transits of the Moon across the local meridian of a place. Since, at perigee-syzygy, the Moon is moving faster in the same direction that the Earth is rotating, an additional catch-up time is required for transit of the Moon, and the length of the lunar day is increased.

The length of the synodic month, on the other hand, is determined by the number of mean solar days between two successive conjunctions of the Moon and Sun, as seen from the Earth. Since the Earth's period of rotation, for the purpose of the present discussion, may be assumed to be constant, the synodic month varies only with the relative orbital motion of the Earth (hence also the apparent motion of the Sun) and that of the Moon as a function of its changing orbital configuration, subject to perturbations.

As the orbital velocities of the Earth and/or the Moon are increased, the necessary catch-up time to achieve the alignment of Earth, Moon, and Sun at syzygy is likewise increased and, coincidentally, the length of the synodic month is increased—as shown in column 8 of table 17. Thus, the synodic month is composed of mean solar days, and may be related also to a given number of tidal days, but the two concepts are not directly connected.

A further distinction for the purpose of clarity should here be made between the concepts of period of revolution, in days, and both angular velocity in orbit and mean daily motion—each of the last usually expressed in °/day. In the common physical case of uniform circular motion with constant angular velocity, as the period of rotation P increases, the value of the unit angular velocity n decreases, and vice versa. In an elliptical astronomical orbit, although P still varies inversely as the *mean* angular velocity $\bar{n}$ throughout the entire revolution of the orbit, and may be computed approximately therefrom, its exact value for any one revolution depends upon a presumably fixed and unperturbed length of the semimajor axis a. (More precisely, P^2 varies directly as a^3.) Any time in a lunar revolution that a varies, P varies accordingly. Therefore, as the instantaneous value of n increases at perigee (-syzygy) and decreases at apogee (-syzygy) the period is not directly affected thereby. Rather, its value is changed by corresponding alterations in the shape of the lunar orbit at these times.

In the case of those months which contain a close alignment of perigee-syzygy, both the NM–NM and FM–FM synodic months become longer when computed between the times of successive apogee-syzygies (see table 17), and the apparent daily motion of the Moon becomes faster in that portion of the orbit bracketing the time of perigee-syzygy. In the apogee-syzygy portion of the orbit, however, a much slower apparent motion of the Moon occurs, and the lengths of the synodic months calculated from perigee-syzygy to perigee-syzygy and containing the time of apogee-syzygy centrally located are considerably shorter than those computed from apogee-syzygy to apogee-syzygy, having the time of perigee-syzygy midway in the period.

It might thus be readily assumed that the relatively high lunar velocity at perigee-syzygy would be compensated for by the comparatively low angular velocity at apogee-syzygy, and that the length of the month would average out unchanged. According to the specific time-referenced positions in orbit from which the data of table 17 are compiled, such is not the case.

Finally, and worthy of special note in the light of ultimately more refined tidal predictions at these times of maximized amplitudes, it will be observed by reference to table 20 that the actual daily angular velocity of the Moon in celestial longitude at proxigee-syzygy ($15.2585°/^d$) is considerably in excess of the assumed mean value ($13.1764°/^d$) presently used in tidal calculations; again, at apogee following even the ordinary syzygy alignment (with perigee at quadrature) given in table 21, the actual daily motion of the Moon ($11.8491°/^d$) is much less than this assumed mean value. Such an average value is far from representative at times of proxigee-syzygy and exogee-syzygy.

Conditions Lengthening the Synodic and Anomalistic Months

To illustrate these relationships clearly, the pertinent lunar data have been tabulated (for double-verification purposes) over a period of time equal to two complete rotations of the line of apsides in the anomalistic cycle of 8.849 tropical years (table 17). In this table, columns 1–2 contain the exact dates of full moons, and columns 5–6 the exact dates of new moons, throughout this period. The changing lengths of the "synodic months" (see the second following paragraph), determined alternatively by the differences between the times of two consecutive full

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*

	Intervals between successive syzygies					Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
1959	Jan. 24.8139			Jan. 9.2319	1959		Jan. 5.833	1959
		29.5569	29.5750			25.42		
	Feb. 23.3708			Feb. 7.8069			Jan. 31.250	
		29.4639	29.6451			26.17		
	Mar. 24.8347			Mar. 9.4521			Feb. 26.417	
		29.3827	29.6931			27.96		
	Apr. 23.2174			Apr. 8.1451			Mar. 26.375	
		29.3215	**29.6958**			28.38		
P-S	May 22.5389			May 7.8410			Apr. 23.750	
		29.2944	29.6542			28.46		
	June 20.8333			June 6.4951			May 22.208	P-S
		29.3146	29.5882			28.33		
	July 20.1479			July 6.0833			June 19.542	
		29.3868	29.5236			28.04		
	Aug. 18.5347			Aug. 4.6069			July 17.583	
		29.5007	29.4729			27.08		
	Sept. 17.0354			Sept. 3.0799			Aug. 13.667	
		29.6299	29.4417			25.04		
	Oct. 16.6653			Oct. 2.5215			Sept. 7.708	
		29.7389	29.4236			27.17		
	Nov. 15.4042			Oct. 31.9451			Oct. 4.875	
		29.7965	29.4201			28.17		
	Dec. 15.2007			Nov. 30.3653	P-S		Nov. 2.042	
		29.7931	29.4326			28.46		
1960	Jan. 13.9938			Dec. 29.7979			Nov. 30.500	P-S
		29.7312	29.4632			28.54		
	Feb. 12.7250			Jan. 28.2611	1960		Dec. 29.042	
		29.6264	29.5056			28.38		
	Mar. 13.3514			Feb. 26.7667			Jan. 26.417	1960
		29.5014	29.5514			27.71		
	Apr. 11.8528			Mar. 27.3181			Feb. 23.125	
		29.3854	29.5882			25.17		
	May 11.2382			Apr. 25.9063			Mar. 19.292	
		29.3049	29.6095			26.50		
	June 9.5431			May 25.5188			Apr. 14.792	
		29.2743	29.6250			27.96		
P-S	July 8.8174			June 24.1438			May 12.750	
		29.2944	**29.6277**			28.33		
	Aug. 7.1118			July 23.7715			June 10.083	
		29.3597	29.6146			28.38		
	Sept. 5.4715			Aug. 22.3861			July 8.458	P-S
		29.4570	29.5813			28.38		
	Oct. 4.9285			Sept. 20.9674			Aug. 5.833	
		29.5701	29.5347			28.04		
	Nov. 3.4986			Oct. 20.5021			Sept. 2.875	
		29.6854	29.4889			27.04		
	Dec. 3.1840			Nov. 18.9910			Sept. 29.917	
		29.7785	29.4583			24.92		
1961	Jan. 1.9625			Dec. 18.4493			Oct. 24.833	
		29.8201	29.4465			27.33		
	Jan. 31.7826			Jan. 16.8958	P-S		Nov. 21.167	

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
		29. 7834	29. 4452			28. 29		
	Mar. 2. 5660			Feb. 15. 3410	1961		Dec. 19. 458	
		29. 6756	29. 4440			28. 50		
	Apr. 1. 2417			Mar. 16. 7854			Jan. 16. 958	P-S
		29. 5368	29. 4493			28. 50		
	Apr. 30. 7785			Apr. 15. 2347			Feb. 14. 458	1961
		29. 4146	29. 4702			28. 29		
	May 30. 1931			May 14. 7049			Mar. 14. 750	
		29. 3333	29. 5152			27. 58		
	June 28. 5264			June 13. 2201			Apr. 11. 333	
		29. 3007	29. 5799			25. 17		
	July 27. 8271			July 12. 8000			May 6. 500	
		29. 3076	29. 6417			26. 62		
P-S	Aug. 26. 1347			Aug. 11. 4417			June 2. 125	
		29. 3472	**29. 6764**			27. 92		
	Sept. 24. 4819			Sept. 10. 1181			June 30. 042	
		29. 4146	29. 6687			28. 33		
	Oct. 23. 8965			Oct. 9. 7868			July 28. 375	
		29. 5091	29. 6292			28. 42		
	Nov. 22. 4056			Nov. 8. 4160			Aug. 25. 792	P-S
		29. 6236	29. 5784			28. 38		
	Dec. 22. 0292			Dec. 7. 9944			Sept. 23. 167	
		29. 7326	29. 5306			28. 12		
1962	Jan. 20. 7618			Jan. 6. 5250	1962		Oct. 21. 292	
		29. 7924	29. 4819			26. 92		
	Feb. 19. 5542			Feb. 5. 0069			Nov. 17. 208	
		29. 7764	29. 4312			24. 79		
	Mar. 21. 3306			Mar. 6. 4382	P-S		Dec. 12. 000	
		29. 6930	29. 3847			27. 58		
	Apr. 20. 0236			Apr. 4. 8229			Jan. 8. 583	1962
		29. 5820	29. 3611			28. 33		
	May 19. 6056			May 4. 1840			Feb. 5. 917	
		29. 4798	29. 3764			28. 50		
	June 18. 0854			June 2. 5604			Mar. 6. 417	P-S
		29. 4014	29. 4347			28. 46		
	July 17. 4868			July 1. 9951			Apr. 3. 875	
		29. 3535	29. 5215			28. 21		
	Aug. 15. 8403			July 31. 5167			May 2. 083	
		29. 3347	29. 6146			27. 46		
	Sept. 14. 1750			Aug. 30. 1312			May 29. 542	
		29. 3479	29. 6882			25. 29		
P-S	Oct. 13. 5229			Sept. 28. 8194			June 23. 833	
		29. 3965	**29. 7257**			26. 58		
	Nov. 11. 9194			Oct. 28. 5451			July 20. 417	
		29. 4750	29. 7257			27. 92		
	Dec. 11. 3944			Nov. 27. 2708			Aug. 17. 333	
		29. 5702	29. 6868			28. 33		
1963	Jan. 9. 9646			Dec. 26. 9576			Sept. 14. 667	
		29. 6548	29. 6132			28. 46		
	Feb. 8. 6194			Jan. 25. 5708	1963		Oct. 13. 125	P-S
		29. 7063	29. 5167			28. 46		
	Mar. 10. 3257			Feb. 24. 0875			Nov. 10. 583	
		29. 7139	29. 4194			28. 12		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
	Apr. 9.0396			Mar. 25.5069			Dec. 8.708	
		29.6854	29.3465			26.62		
	May 8.7250			Apr. 23.8535	P-S		Jan. 4.333	
		29.6299	29.3132			24.96		
	June 7.3549			May 23.1667			Jan. 29.292	1963
		29.5590	29.3236			27.71		
	July 6.9139			June 21.4903			Feb. 26.000	
		29.4826	29.3729			28.33		
	Aug. 5.3965			July 20.8632			Mar. 26.333	
		29.4188	29.4528			28.46 ●		
	Sept. 3.8153			Aug. 19.3160			Apr. 23.792	P-S
		29.3819	29.5528			28.38		
	Oct. 3.1972			Sept. 17.8688			May 22.167	
		29.3834	29.6611			28.17		
	Nov. 1.5806			Oct. 17.5299			June 19.333	
		29.4159	29.7556			27.42		
P-S	Nov. 30.9965			Nov. 16.2854			July 16.750	
		29.4646	29.8028			25.25		
	Dec. 30.4611			Dec. 16.0882			Aug. 11.000	
		29.5132	29.7757			26.67		
1964	Jan. 28.9743			Jan. 14.8639	1964		Sept. 6.667	
		29.5535	29.6792			27.96		
	Feb. 27.5278			Feb. 13.5431			Oct. 4.625	
		29.5896	29.5500			28.38		
	Mar. 28.1174			Mar. 14.0931			Nov. 2.000	
		29.6257	29.4333			28.54 ●		
	Apr. 26.7431			Apr. 12.5264			Nov. 30.542	P-S
		29.6520	29.3500			28.46		
	May 26.3951			May 11.8764			Dec. 29.000	
		29.6528	29.3062			28.04		
	June 25.0479			June 10.1826	P-S		Jan. 26.042	1964
		29.6174	29.2973			26.29		
	July 24.6653			July 9.4799			Feb. 21.333	
		29.5611	29.3236			25.33		
	Aug. 23.2264			Aug. 7.8035			Mar. 17.667	
		29.5035	29.3875			27.75		
	Sept. 21.7299			Sept. 6.1910			Apr. 14.417	
		29.4687	29.4896			28.25		
	Oct. 21.1986			Oct. 5.6806			May 12.667	
		29.4563	29.6229			28.42 ●		
	Nov. 19.6549			Nov. 4.3035			June 10.083	P-S
		29.4576	29.7514			28.38		
P-S	Dec. 19.1125			Dec. 4.0549			July 8.458	
		29.4556	**29.8250**			28.17		
1965	Jan. 17.5681			Jan. 2.8799	1965		Aug. 5.625	
		29.4507	29.8118			27.46		
	Feb. 16.0188			Feb. 1.6917			Sept. 2.083	
		29.4562	29.7222			25.12		
	Mar. 17.4750			Mar. 3.4139			Sept. 27.208	
		29.4854	29.6007			26.71		

Table 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
	Apr. 15.9604			Apr. 2.0146			Oct. 23.917	
		29.5347	29.4826			28.08		
	May 15.4951			May 1.4972			Nov. 21.000	
		29.5882	29.3868			28.46		
	June 14.0833			May 30.8840			Dec. 19.458	P-S
		29.6264	29.3195			28.58		
	July 13.7097			June 29.2035			Jan. 17.042	1965
		29.6477	29.2861			28.42		
	Aug. 12.3556			July 28.4896	P-S		Feb. 14.458	
		29.6250	29.2958			27.92		
	Sept. 10.9806			Aug. 26.7854			Mar. 14.375	
		29.6125	29.3521			26.08		
	Oct. 10.5931			Sept. 25.1375			Apr. 9.458	
		29.5847	29.4542			25.58		
	Nov. 9.1778			Oct. 24.5917			May 5.042	
		29.5458	29.5819			27.71		
	Dec. 8.7236			Nov. 23.1736			June 1.750	
		29.4965	29.7035			28.25		
1966	Jan. 7.2201			Dec. 22.8771			June 30.000	
		29.4452	29.7805			28.38		
P-S	Feb. 5.6653			Jan. 21.6576			July 28.375	P-S
		29.4083	**29.7938**			28.42		
	Mar. 7.0736			Feb. 20.4514	1966		Aug. 25.792	
		29.3945	29.7479			28.17		
	Apr. 5.4681			Mar. 22.1993			Sept. 22.958	
		29.4076	29.6590			27.50		
	May 4.8757			Apr. 20.8583			Oct. 20.458	
		29.4444	29.5466			24.88		
	June 3.3201			May 20.4049			Nov. 14.333	
		29.4973	29.4347			26.92		
	July 2.8174			June 18.8396			Dec. 11.250	
		29.5618	29.3486			28.17		
	Aug. 1.3792			July 18.1882			Jan. 8.417	1966
		29.6305	29.3035			28.50		
	Aug. 31.0097			Aug. 16.4917			Feb. 5.917	P-S
		29.6903	29.3097			28.54		
	Sept. 29.7000			Sept. 14.8014	P-S		Mar. 6.458	
		29.7174	29.3597			28.33		
	Oct. 29.4174			Oct. 14.1611			Apr. 3.792	
		29.6944	29.4410			27.79		
	Nov. 28.1118			Nov. 12.6021			May 1.583	
		29.6271	29.5326			26.00		
	Dec. 27.7389			Dec. 12.1347			May 27.583	
		29.5396	29.6195			25.75		
1967	Jan. 26.2785			Jan. 10.7542	1967		June 22.333	
		29.4604	29.6930			27.71		
	Feb. 24.7389			Feb. 9.4472			July 20.042	
		29.4007	29.7403			28.25		
P-S	Mar. 26.1396			Mar. 11.1875			Aug. 17.292	
		29.3632	**29.7438**			28.42		
	Apr. 24.5028			Apr. 9.9313			Sept. 14.708	P-S
		29.3465	29.6909			28.42		
	May 23.8493			May 9.6222			Oct. 13.125	
		29.3570	29.5959			28.25		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
	June 22.2063			June 8.2181			Nov. 10.375	
		29.4048	29.4909			27.38		
	July 21.6111			July 7.7090			Dec. 7.750	
		29.4910	29.4084			24.67		
	Aug. 20.1021			Aug. 6.1174			Jan. 1.417	1967
		29.6062	29.3673			27.21		
	Sept. 18.7083			Sept. 4.4847			Jan. 28.625	
		29.7160	29.3653			28.25		
	Oct. 18.4243			Oct. 3.8500			Feb. 25.875	
		29.7792	29.3924			28.46		
	Nov. 17.2035			Nov. 2.2424	P-S		Mar. 26.333	P-S
		29.7701	29.4312			28.46		
	Dec. 16.9736			Dec. 1.6736			Apr. 23.792	
		29.7014	29.4785			28.29		
1968	Jan. 15.6750			Dec. 31.1521			May 22.083	
		29.6049	29.5354			27.75		
	Feb. 14.2799			Jan. 29.6875			June 18.833	
		29.5069	29.6014			26.00		
	Mar. 14.7868			Feb. 28.2889	1968		July 14.833	
		29.4160	29.6618			25.79		
	Apr. 13.2028			Mar. 28.9507			Aug. 9.625	
		29.3423	**29.6896**			27.71		
P-S	May 12.5451			Apr. 27.6403			Sept. 6.333	
		29.2980	29.6722			28.25		
	June 10.8431			May 27.3125			Oct. 4.583	
		29.2944	29.6215			28.50		
	July 10.1375			June 25.9340			Nov. 2.083	P-S
		29.3438	29.5591			28.50		
	Aug. 8.4813			July 25.4931			Nov. 30.583	
		29.4409	29.5048			28.21		
	Sept. 6.9222			Aug. 23.9979			Dec. 28.792	
		29.5688	29.4667			27.21		
	Oct. 6.4910			Sept. 22.4646			Jan. 25.000	1968
		29.6930	29.4417			24.67		
	Nov. 5.1840			Oct. 21.9063			Feb. 18.667	
		29.7799	29.4284			27.40		
	Dec. 4.9639			Nov. 20.3347			Mar. 17.063	
		29.8055	29.4285			28.23		
1969	Jan. 3.7694			Dec. 19.7632	P-S		Apr. 14.292	
		29.7695	29.4444			28.42		
	Feb. 2.5389			Jan. 18.2076	1969		May 12.708	P-S
		29.6819	29.4771			28.42		
	Mar. 4.2208			Feb. 16.6847			June 10.125	
		29.5611	29.5181			28.25		
	Apr. 2.7819			Mar. 18.2028			July 8.375	
		29.4362	29.5583			27.75		
	May 2.2181			Apr. 16.7611			Aug. 5.125	
		29.3368	29.5910			25.96		
	May 31.5549			May 16.3521			Aug. 31.083	
		29.2812	29.6125			25.75		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
P-S	June 29. 8361			June 14. 9646			Sept. 25. 833	
		29. 2792	29. 6271			27. 79		
	July 29. 1153			July 14. 5917			Oct. 23. 625	
		29. 3243	**29. 6284**			28. 38		
	Aug. 27. 4396			Aug. 13. 2201			Nov. 21. 000	
		29. 4090	29. 6105			28. 50		
	Sept. 25. 8486			Sept. 11. 8306		●	Dec. 19. 500	P-S
		29. 5160	29. 5722			28. 50		
	Oct. 25. 3646			Oct. 11. 4028			Jan. 17. 000	1969
		29. 6312	29. 5222			28. 17		
	Nov. 23. 9958			Nov. 9. 9250			Feb. 14. 167	
		29. 7375	29. 4799			26. 92		
	Dec. 23. 7333			Dec. 9. 4049			Mar. 13. 083	
		29. 8056	29. 4534			24. 92		
1970	Jan. 22. 5389			Jan. 7. 8583	1970		Apr. 7. 000	
		29. 8076	29. 4431			27. 46		
	Feb. 21. 3465			Feb. 6. 3014	P-S		May 4. 458	
		29. 7320	29. 4368			28. 17		
	Mar. 23. 0785			Mar. 7. 7382			June 1. 625	
		29. 6034	29. 4354			28. 38		
	Apr. 21. 6819			Apr. 6. 1736		●	June 30. 000	P-S
		29. 4695	29. 4458			28. 38		
	May 21. 1514			May 5. 6194			July 28. 375	
		29. 3680	29. 4792			28. 25		
	June 19. 5194			June 4. 0986			Aug. 25. 625	
		29. 3132	29. 5389			27. 83		
	July 18. 8326			July 3. 6375			Sept. 22. 458	
		29. 3035	29. 6118			25. 71		
P-S	Aug. 17. 1361			Aug. 2. 2493			Oct. 18. 167	
		29. 3292	29. 6688			25. 92		
	Sept. 15. 4653			Aug. 31. 9181			Nov. 13. 083	
		29. 3833	**29. 6875**			27. 92		
	Oct. 14. 8486			Sept. 30. 6056			Dec. 11. 000	
		29. 4632	29. 6645			28. 42		
	Nov. 13. 3118			Oct. 30. 2701			Jan. 8. 417	1970
		29. 5660	29. 6153			28. 54 ●		
	Dec. 12. 8778			Nov. 28. 8854			Feb. 5. 958	P-S
		29. 6785	29. 5611			28. 46		
1971	Jan. 11. 5563			Dec. 28. 4465			Mar. 6. 417	
		29. 7645	29. 5091			28. 04		
	Feb. 10. 3208			Jan. 26. 9556	1971		Apr. 3. 458	
		29. 7861	29. 4534			26. 71		
	Mar. 12. 1069			Feb. 25. 4090	P-S		Apr. 30. 167	
		29. 7341	29. 3993			25. 17		
	Apr. 10. 8410			Mar. 26. 8083			May 25. 333	
		29. 6340	29. 3598			27. 42		
	May 10. 4750			Apr. 25. 1681			June 21. 750	
		29. 5278	29. 3541			28. 17		
	June 9. 0028			May 24. 5222			July 19. 917	
		29. 4396	29. 3931			28. 38		
	July 8. 4424			June 22. 9153			Aug. 17. 292	P-S
		29. 3791	29. 4708			28. 42 ●		
	Aug. 6. 8215			July 22. 3861			Sept. 14. 708	
		29. 3473	29. 5681			28. 33		
	Sept. 5. 1688			Aug. 20. 9542			Oct. 13. 042	
		29. 3451	29. 6590			27. 79		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
P-S	Oct. 4.5139			Sept. 19.6132			Nov. 9.833	
		29.3750	29.7201			25.42		
	Nov. 2.8889			Oct. 19.3333			Dec. 5.250	
		29.4368	**29.7403**			26.17		
	Dec. 2.3257			Nov. 18.0736			Dec. 31.417	
		29.5215	29.7202			28.00		
	Dec. 31.8472			Dec. 17.7938			Jan. 28.417	1971
		29.6097	29.6590			28.46		
1972	Jan. 30.4569			Jan. 16.4528	1972		Feb. 25.875	P-S
		29.6764	29.5673			28.50 ●		
	Feb. 29.1333			Feb. 15.0201			Mar. 26.375	
		29.7035	29.4625			28.38		
	Mar. 29.8368			Mar. 15.4826			Apr. 23.750	
		29.6938	29.3723			27.96		
	Apr. 28.5306			Apr. 13.8549	P-S		May 21.708	
		29.6555	29.3173			26.71		
	May 28.1861			May 13.1722			June 17.417	
		29.5958	29.3070			25.21		
	June 26.7819			June 11.4792			July 12.625	
		29.5264	29.3396			27.42		
	July 26.3083			July 10.8188			Aug. 9.042	
		29.4570	29.4076			28.17		
	Aug. 24.7653			Aug. 9.2264			Sept. 6.208	
		29.4062	29.5014			28.42		
	Sept. 23.1715			Sept. 7.7278			Oct. 4.625	P-S
		29.3875	29.6111			28.46 ●		
	Oct. 22.5590			Oct. 7.3389			Nov. 2.083	
		29.4042	29.7174			28.25		
P-S	Nov. 20.9632			Nov. 6.0563			Nov. 30.458	
		29.4431	29.7937			27.87		
	Dec. 20.4063			Dec. 5.8500			Dec. 28.208	
		29.4881	**29.8042**			25.00		
1973	Jan. 18.8944			Jan. 4.6542	1973		Jan. 22.208	1972
		29.5271	29.7368			26.58		
	Feb. 17.4215			Feb. 3.3910			Feb. 17.792	
		29.5598	29.6139			28.08		
	Mar. 18.9813			Mar. 5.0049			Mar. 16.875	
		29.5958	29.4847			28.38		
	Apr. 17.5771			Apr. 3.4896			Apr. 14.250	P-S
		29.6298	29.3820			28.46 ●		
	May 17.2069			May 2.8715			May 12.708	
		29.6507	29.3188			28.29		
	June 15.8576			June 1.1903	P-S		June 10.000	
		29.6396	29.2951			27.96		
	July 15.4972			June 30.4854			July 7.958	
		29.5979	29.3056			26.67		
	Aug. 14.0951			July 29.7910			Aug. 3.625	
		29.5410	29.3514			25.21		
	Sept. 12.6361			Aug. 28.1424			Aug. 28.833	
		29.4952	29.4368			27.46		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
	Oct. 12.1313			Sept. 26.5792			Sept. 25.292	
		29.4708	29.5576			28.21		
	Nov. 10.6021			Oct. 26.1368			Oct. 23.500	
		29.4632	29.6930			28.50		
	Dec. 10.0653			Nov. 24.8299			Nov. 21.000	P-S
		29.4597	29.8000			28.54		
P-S	Jan. 8.5250			Dec. 24.6299			Dec. 19.542	
		29.4500	**29.8298**			28.33		
1974	Feb. 6.9750			Jan. 23.4597	1974		Jan. 16.875	1973
		29.4438	29.7722			27.58		
	Mar. 8.4188			Feb. 22.2319			Feb. 13.458	
		29.4562	29.6597			24.88		
	Apr. 6.8750			Mar. 23.8917			Mar. 10.333	
		29.4965	29.5368			26.83		
	May 6.3715			Apr. 22.4285			Apr. 6.167	
		29.5521	29.4285			28.08		
	June 4.9236			May 21.8569			May 4.250	
		29.6042	29.3486			28.33		
	July 4.5278			June 20.2056			June 1.583	P-S
		29.6368	29.2993			28.42		
	Aug. 3.1646			July 19.5049	P-S		June 30.000	
		29.6444	29.2882			28.29		
	Sept. 1.8090			Aug. 17.7931			July 28.292	
		29.6341	29.3215			28.00		
	Oct. 1.4431			Sept. 16.1146			Aug. 25.292	
		29.6118	29.4028			26.62		
	Oct. 31.0549			Oct. 15.5174			Sept. 20.917	
		29.5770	29.5194			25.12		
	Nov. 29.6319			Nov. 14.0369			Oct. 16.042	
		29.5285	29.6472			27.58		
	Dec. 29.1604			Dec. 13.6840			Nov. 12.625	
		29.4709	29.7466			28.29		
1975	Jan. 27.6313			Jan. 12.4306			Dec. 10.917	
		29.4208	**29.7895**			28.54		
P-S	Feb. 26.0521			Feb. 11.2201	1975		Jan. 8.458	P-S
		29.3896	29.7709			28.54		
	Mar. 27.4417			Mar. 12.9910			Feb. 6.000	1974
		29.3882	29.7028			28.25		
	Apr. 25.8299			Apr. 11.6938			Mar. 6.250	
		29.4139	29.6013			27.42		
	May 25.2438			May 11.2951			Apr. 2.667	
		29.4604	29.4889			25.00		
	June 23.7042			June 9.7840			Apr. 27.667	
		29.5236	29.3896			26.88		
	July 23.2278			July 9.1736			May 24.542	
		29.5972	29.3243			28.04		
	Aug. 21.8250			Aug. 7.4979			June 21.583	
		29.6681	29.3070			28.33		
	Sept. 20.4931			Sept. 5.8049	P-S		July 19.917	P-S
		29.7194	29.3361			28.38		
	Oct. 20.2125			Oct. 5.1410			Aug. 17.292	
		29.7236	29.4041			28.38		
	Nov. 18.9361			Nov. 3.5451			Sept. 14.667	
		29.6750	29.4896			28.00		

TABLE 17.—*Increase in the Lengths of the Synodic and Anomalistic Months With Proximity to Those Months Containing Perigee-Syzygy Alignments*—Continued

Intervals between successive syzygies						Intervals between successive perigees		
Year	Date FM	Synodic month FM–FM	Synodic month NM–NM	Date NM	Year	Anomalistic month P–P	Date P	Year
	Dec. 18. 6111			Dec. 3. 0347			Oct. 12. 667	
						26. 50		
							Nov. 8. 167	
						25. 12		
							Dec. 3. 292	
						27. 71		
							Dec. 31. 000	
						28. 38		
							Jan. 28. 375	1975
						28. 54 ●		
							Feb. 25. 917	P-S
						28. 46		
							Mar. 26. 375	
						28. 17		
							Apr. 23. 542	
						27. 29		
							May 20. 833	
						25. 08		
							June 14. 917	
						26. 92		
							July 11. 833	
						28. 00		
							Aug. 8. 833	
						28. 33		
							Sept. 6. 167	P-S
						28. 46 ●		
							Oct. 4. 625	
						28. 42		
							Nov. 2. 042	
						28. 00		
							Nov. 30. 042	
						26. 12		
							Dec. 26. 167	

moons and two consecutive new moons, are given in columns 3 and 4.

Because it is desired to determine the length of that synodic month which most nearly brackets each case of perigee-syzygy, it becomes necessary to consider the period of time between two succeeding occurrences of the *opposite* phase of syzygy. That is, to determine the length of the synodic month which contains, midway in the month, a perigee-syzygy alignment at full moon, it is necessary to calculate the period of elapsed time between the most closely bracketing new moons. To determine the length of the synodic month in which the date of a perigee-syzygy at new moon is centrally located, the procedure involves taking the difference in time between successive full moons.

A synodic month is, by convention,[b] defined as the period of time between new moon and new moon. Because of the shift in dates and in the position of the Moon in its elliptical orbit, different values for the length of the synodic period will be obtained if the month is reckoned from full moon to full moon. The possibility of mutual commensurability varies as either the synodic or anomalistic periods vary. The lengths of the synodic months will show either a maximum or minimum value according as the period chosen contains the date of perigee or apogee, respectively. For analytic purposes, this nonconventional procedure of computing both periods is used here.

[b] See *Explanatory Supplement to the Astronomical Ephemeris and The American Ephemeris and Nautical Almanac,* London, 1961, p. 107.

Maximized Lengths of Those Months Bracketing Perigee-Syzygy

The lengths of synodic months listed in table 17 reveal the considerably different values which pertain for those dates which bracket a date of perigee-syzygy compared with those which bracket an apogee-syzygy situation. For every condition of full moon occurring nearly coincidentally with perigee, the next following (or preceding) new moon will occur reasonably close to the time of apogee one-half of an anomalistic month later (or earlier). The interval represented is ½ of 27.55455=13.77728, while the exact alternation of syzygy phases occurs in ½ of the synodic month of 29.53059 days=14.76530 days. This gives a difference of only 0.98802 day between new moon and apogee in the new position. In terms of the limit of ±1 day between components established for a standard perigee-syzygy situation (table 16), the latter case can, with consistency, be classified as a typical apogee-syzygy alignment.

From immediately adjacent values in columns 3 and 4 of table 17, it will be noted that each condition of *perigee*-syzygy at *full* moon (marked by a maximum length of the synodic month) is very nearly matched, in the next succeeding or preceding half month, by a near-coincidence of *apogee*-syzygy at *new* moon, (having a minimum length of the month) and vice versa. In this 2-week interval, the Moon revolves in its orbit through 180° from alignment with the Earth and Sun at perigee-syzygy to an approximate alignment with Earth and Sun again at apogee-syzygy. Since the Sun has moved only about 14° of arc from the line of apsides in this same period, its perturbative influence is still active thereon.

Of most relevant importance to the present discussion, however, is the fact that, because the Moon's velocity in orbit at apogee-syzygy is considerably slower than at perigee-syzygy, the necessary catch-up motion by the rotating Earth is less at the apogee position. The duration of each lunar day near the time of apogee-syzygy is less, and the lengths of both the anomalistic and synodic months bracketing apogee-syzygy are shorter than those bracketing perigee-syzygy.

Cycles of Alternation in Perigee-Syzygy Alignments

As noted later in this same section, an almost universal tendency exists for cases of close perigee-syzygy alignment to occur in pairs, two in contiguous anomalistic months, followed by two more within about a half-year of the first. An alternate choice of cyclical relationship therefore exists between these two sets of semiannually occurring, noncontiguous cases of perigee-syzygy. One element of each pair will, however, invariably have a smaller separation-interval between perigee and syzygy than the other. According to the procedure here adopted for establishing the most meaningful perigee-syzygy cycle, the semiannual period is defined as the difference in time between those cases of perigee-syzygy alignment in each of the two pairs having the smallest separation, in hours, between their individual components.

The near-coincidence of perigee with syzygy (either new moon or full moon) will, because of recurring, approximately commensurable relationships between the synodic and anomalistic months, result in approximate agreement again within definite cycles. Short-period repetitions will occur (at the same lunar phase) an average between one anomalistic and one synodic month earlier or later; also (at opposite lunar phases) separated from the first case by an interval established by the average between either 6.25 (to 6.5) or 7.25 (to 7.5) anomalistic and synodic months. The average must be taken between the actual (not mean) lengths of the synodic and anomalistic months, such as are given in table 17. (Cf., further page 25, last paragraph of Explanatory Comments to table 1, and the bracketed repetitions of tidal flooding in table 1; also table 4a.) In the terms of reference used, the first set of two values involving an approximate 6-month period applies to the situation in which two cases of perigee-syzygy—each possessing the smaller separation-interval within its own pair—are located consecutively within approximately one-half year of each other in the comprehensive perigee-syzygy series of table 16. The second, 7.25- to 7.5-month period applies to those cases separated by one or more intervening perigee-syzygy occurrences. The 7.5-month pair possesses the smallest, the intervening cases the largest separation-intervals in their respective groups.

The range from 0.25 to 0.5 month in each case connotes an approximate average rather than a specific value. It is due to the varying periodicities (resulting from altered orbital eccentricities) which may span two cases of close perigee-spring alignment. For convenience, only the 0.5-month values in each set hereafter will be referred to, as more indicative of the accompanying change from new moon to full moon or the reverse. It will be implicitly understood that, wherever this one value is cited to the exclusion of the other, a several-day variation around either 6.25 to 6.5 or 7.25 to 7.5 months as defined above may actually be represented in the exact interval between successive cases of perigee-syzygy.

As seen in table 16, a perigee-syzygy situation at new moon becomes a perigee-syzygy situation at full moon 6.5 or 7.5 months later (or earlier), with the two remaining combinations of perigee-quadrature occurring approximately halfway inbetween. A more detailed analysis of the exact cycles and relationships involved, which are dependent upon variations in the lengths of the synodic and anomalistic months and certain other astronomically varying influences, is presented in the following pages.

The Meaning and Relationships of High and Low Maxima in the Lengths of the Lunar Months

With each repetition of a close perigee-syzygy alignment, the Moon's orbital velocity accelerates to one of its maxima, and the Earth's required rotational catch-up times reach corresponding maximum values. Simultaneously, the lengths of the synodic months centered around these perigee-syzygy positions increase toward their own maxima.

This increase in the lengths of the synodic months (and their constituent tidal days) to recurrent maxima corresponding to the times of perigee-syzygy gives support to the premise variously enunciated throughout this monograph: (1) that the augmentation in height of perigean spring tides is produced by the various reinforcing forces enumerated in chapters 3–4; and (2) these forces are contributed to through a prolongation of their period of maximum action, caused by a coincident increase in various astronomical catch-up motions and (as will be seen later in this same chapter) sometimes also by increased individual motions in right ascension.

The lengths of successive anomalistic months listed in table 17 contain the effects of perturbations of the Moon's line of apsides at both perigee and apogee as the apparent solar motion brings the Sun into coincidence with this line; also the retrograde motion of the line of apsides induced at both longitudinal positions of the Sun which make an angle of 90° with respect to the lunar line of apsides.

Columns 7, 8, and 9 in this table show the influence of the changing speed of the Moon in orbit as it affects the length of the anomalistic month. When the Moon's motion is accelerated at time of perigee-syzygy, the Earth's rotation must necessarily catch up. The length of the anomalistic month which contains the coincidence of perigee-syzygy is proportionately increased.

The dates of the closest alignments of perigee-syzygy are indicated in column 9 by the letters P-S. It will be noted that, very nearly opposite each of these P-S symbols, the figure in column 7 representing the length of the anomalistic month also reaches a corresponding maximum—usually one of two possible maximum values in the calendar year. (There are necessarily two such maxima within each 15 anomalistic months.) The circumstance that the lengths of these particular anomalistic months within each approximate 15-month period are increased to a maximum value confirms the fact that the rotational catch-up motions of the Earth are the greatest at these times.

For each successive approach to, and recession from, a case of close perigee-syzygy alignment, a set of square brackets encloses all values of the anomalistic month in column 7 which are in excess of the standard mean value (27.554551^{d}) used in astronomy. In the long-period, net motion of perigee depicted in figures 28, 30, and 32 (as opposed to its short-period motion occurring immediately in the vicinity of perigee-syzygy) another fact is noteworthy in this table: During each of the anomalistic months contained within the square brackets, the *net* motion of perigee is forward; during the remaining anomalistic months (whose lengths are all less than the established mean value) the net motion of perigee is retrograde. The anomalistic month (or average of two equal anomalistic months) of longest duration in each bracketed series is indicated by a bold dot (bullet) placed directly to the right of its value in column 7.

It is, of course, possible to obtain the separation-interval representing the actual near-coincidence in time between the occurrences of perigee and syzygy at each such alignment by simply taking the difference between columns 2 and 8 of this table for the appropriate P-S date. The values should be subtracted in the sense perigee date minus syzygy date to maintain consistency in algebraic sign. Because of the two-component relationship required to establish the condition of perigee-syzygy, a close (if not exact) correlation also will be observed between any synodic month of maximum length and the anomalistic month of maximum length occurring in the same close proximity to perigee-syzygy. The *maximum* lengths of the synodic months determined between successive occurrences of both new moon and full moon are set in boldface in columns 3 and 4. By noting the number of days separating each succeeding boldface value, the approximate 6.5 or 7.5-month time span between consecutive alignments of perigee-syzygy is immediately evident. The typical alternation from perigee-syzygy at new moon to perigee-syzygy at full moon can be seen by comparing columns 7, 8, and 9 with columns 3 and 4 and 2 or 5, respectively.

Supporting a previous statement regarding the closely related sequence of perigee-syzygy and apogee-syzygy, the maximum length of a synodic month is inevitably accompanied in the adjoining column—and within a period not to exceed 2 weeks earlier or later—by a corresponding minimum. Inherent within the effects of solar perturbations are those altering the lunar period of revolution. Consistent with such dynamic influences, the varying lengths of the synodic months considered as a whole are, of course, a function of their separation in time from perigee-syzygy. Likewise, individual variations in the maximum lengths of the synodic months are a function of the smallness of the separation-interval between perigee and syzygy, the synodic (and anomalistic) months becoming longer as this separation-interval becomes shorter.

1. Variation in Length of the Anomalistic Month

The mean value of the anomalistic month is based upon an assumed mean motion of the Moon *with respect to perigee* amounting to $13.176396°/^{d}—0.111404°/^{d}= 13.064992°/^{d}$. However, because of the increased angular velocity of the Moon at perigee-syzygy, while the Moon is close to this position the Earth requires a small extra portion of each day's rotation to catch up with the Moon and enable it to transit the meridian to complete a lunar day. The maximum absolute angular velocities of the Moon (occurring at proxigee-syzygy) can be as high as 15.4°/day.

It is obvious that the necessary catch-up motion of the rotating Earth resulting from such accelerated motions of the Moon can account for the consistent lengths in excess of that of the mean anomalistic month found in the case of those months which contain a very close perigee-syzygy alignment.

At the same time, a small additional modification is introduced by the net, long-term progression of perigee. The anomalistic month is measured from perigee to perigee. It therefore contains the extra catch-up motion due to the net forward motion of perigee, but calculated for an assumed mean rate of only +0.111404°/day. Accordingly, the true anomalistic month also will be lengthened to a slight extent because of the extra motion required for the Moon to catch up with the greater net forward motion of perigee during those anomalistic months bracketing close perigee-syzygy alignments. The relative lengthening of the anomalistic month will be more, the larger is the net forward motion of perigee with respect to its assumed mean motion.

2. Variation in Length of the Synodic Month

On the other hand, the synodic month is ordinarily measured from new moon, which implies an alignment of the Moon with the Sun. The synodic month by definition already contains the effect of the Moon's catch-up motion with the Sun, viewed from the rotating Earth. Its period is measured in terms of the extra number of rotations of the Earth required to achieve the simultaneous meridian transit of the two bodies. The resulting mean value is based upon an assumed mean daily synodic motion of the Moon amounting to $13.176396°/^{d}— 0.985647°/^{d}=12.190749°/^{d}$.

In this evaluation of the synodic month, the Sun is assumed to move with a mean apparent angular velocity of +0.985647°/day. In the Sun's apparent motion, the variations from its mean value are much smaller than those of the Moon from its mean angular orbital velocity. This is due both to the smaller magnitude of the Sun's mean motion and the smaller daily variations therefrom which are cumulatively totaled. (In addition, the variations in the lunar orbital velocity between perihelion and aphelion are of too small a magnitude to have any influence in this connection.)

Consequently, the maximum variations in the length of the synodic month are considerably less than those in the anomalistic month. The greatest individual values for the length of the synodic month will bracket a perigee-syzygy alignment near the time of perihelion (in accordance with the Sun's greater apparent motion then). The smallest values will occur bracketing an apogee-syzygy situation near aphelion. As a direct corollary, the maximum difference of 0.5555 day in the lengths of the synodic months appearing in this table exists between the months June–July 1960 and Jan.–Feb. 1964 corresponding to periods near aphelion and perihelion, respectively

The Correlation Between Smaller Perigee-Syzygy Separation-Intervals and Longer Months

From a detailed analysis of table 17, various pertinent relationships may be summarized.

1. Over any reasonably short span of time, it is apparent that: (a) the total number of lunar days in corre-

sponding synodic and anomalistic months (a factor determined by the relative orbital motion of the Moon and the necessity for the rotating Earth to catch up on this motion); and (b) the individual lengths of the lunar days contained in each month (again determined by the Moon's changing orbital velocity, as well as relative motion in right ascension) must vary together.

The anomalistic months bracketed in table 17 are grouped around those dates on which perigee and syzygy are in close alignment (the separation-intervals for all examples labeled "P-S" are $\leq 11^h$). These months are therefore, not only lengthened, but their constituent days are made longer at perigee-syzygy.

2. The lengths of both the synodic and anomalistic months vary in inverse proportion to the separation-interval between perigee and syzygy.

3. The chance for coincidence between perigee and syzygy exists twice a month in terms of either new moon or full moon in synodic months but (except for one calendar month in each year with perigee located both at the beginning and end) occurs only once each month in connection with anomalistic months. The two types of months regain a close commensurability, once it has been established, after periods of approximately 28.5, 190, and 219 days.[c]

4. The solar parallactic inequality previously has been described as a condition in which, by virtue of closer distance, the gravitational attraction of the Sun is exerted to a greater extent upon the Moon as it reaches its position of solar perigee once each year about January 2–4. The Moon is then slowed down in its orbit around the Earth as the result of a partial reduction of the Earth's gravitational attraction. This influence is not, however, of a magnitude which is critical in the changing lengths of the synodic months where these are carried to only four decimal places, in days. The decrease in the Sun's daily apparent motion between the position of perihelion (close to that of solar perigee) and aphelion (close to solar apogee) is only some 3′–4′ in celestial longitude.[d]

[c] More exact cycles of commensurability, for predicting a return to similar tide-raising conditions, based upon a number of astronomical variables, including that of perigee-syzygy, are: 28.981403^d, 162.502866^d, 191.484268^d, 205.892318^d, 355.022184^d, and 384.003587^d.

[d] The coordinate of celestial longitude is carefully selected since the apparent daily motion of the Sun in *right ascension* is affected not only by the Earth's position with respect to perihelion and aphelion (i.e., the solar parallactic inequality) but by the declination of the Sun. The resultant daily motion in α varies throughout the year according to the same pattern as the equation of time.

ANALYSIS OF THE RELATIVE GAINS IN THE LENGTHS OF THE ANOMALISTIC AND SYNODIC MONTHS CONTAINING A CLOSE PERIGEE-SYZYGY ALIGNMENT

1. *Anomalistic Month*

(a) The anomalistic month is defined as the period of time between two successive passages of the Moon through perigee.

(b) During the period of one revolution of the Moon around the Earth from alignment in longitude with a given star to alignment with that same star again (i.e., the sidereal month), the position of perigee has itself moved forward an average distance of $27.321661^d \times 0.111404°/^d$ or $3.043742°$.

(c) The Moon must *revolve* through this extra angular distance to catch up with the position of perigee and complete the anomalistic month.

(d) In addition, in order to achieve a meridian transit of the Moon (and Sun) at perigee-syzygy, an observing position on the Earth must *rotate* through an additional angle to catch up with this extra forward motion of the Moon in that part of the orbit where it is revolving the fastest.

(e) An increased period of time is required for the rotating Earth to achieve such a catch-up motion, and the lengths of the lunar (and tidal) days are extended.

(f) Significantly, the Moon must pass over this extra segment of its orbit where it is moving the fastest (i.e., immediately following perigee) a second time in order to catch up with perigee. The extra period of catch-up motion by the rotating Earth while the Moon is traveling at its fastest velocity contributes to the number of days or decimal parts thereof in all anomalistic months. This is especially true where the perigee distance is greatly reduced by a very near-coincidence between perigee and syzygy and the Moon's velocity at this time is increased considerably in proportion.

2. *Synodic Month*

(a) The synodic month ordinarily is defined as the period between two consecutive alignments of the Moon and Sun in celestial longitude at the instants of lunar conjunction (i.e., the period from *new moon* to *new moon*). However, in establishing certain relevant facts as part of the quantitative analysis of this section, both the foregoing and an alternate definition involving the period between *full moons* have been used.

A salient factor exists in this dual method of interpretation: Under either of the two alternate definitions chosen (new moon to new moon, or full moon to full moon) the starting and ending positions in each synodic month also have been selected as opposite in the lunar orbit from the position of perigee-syzygy and, accordingly, at the apogee end of the orbit. The effect of any one perigee-syzygy alignment is thus most accurately bracketed.

(b) While the Moon revolves through one sidereal month with respect to the stars, the Sun advances in its apparent annual motion through approximately 26.929513°, assuming a mean rate of $0.985647°/^d$.

(c) In contrast to the example for the anomalistic month, the necessary catch-up motion by the rotating Earth to complete a transit of the Moon and Sun together at either conjunction or opposition occurs while the Moon is moving at its slowest velocity near apogee.

(d) Furthermore, the segment of the Moon's orbit over which it must pass a second time in catching up with the changing apparent position of the Sun to complete the synodic month is that portion immediately following apogee in which the Moon is traveling at its slowest velocity.

(e) Accordingly, the necessary catch-up time by a position on the rotating Earth to complete the synodic month is not as great as that required under the concept of the anomalistic month, and the latter shows a greater gain in length than the former. The increase in the length of the synodic month containing a close perigee-syzygy alignment, although significant (about 0.6 day), is less than one-sixth the increase in an anomalistic month (as much as 3.9 days) under the same circumstances.

This explanation accounts both for the indicated variations in the length of the synodic month and the fact that, with the positioning of perihelion and aphelion in the present astronomical epoch, the winter months are invariably a significant portion of an hour longer than the summer months, even without the combined influence of perigee-syzygy noted above. This circumstance is of related but mainly academic interest in chapters 7 and 8 in terms of the greatest frequency of tidal flooding accompanying winter storms.

Prolongation of a Small Separation-Interval at Close Perigee-Syzygy Alignments

In the book *Waves and Tides* by R. C. H. Russell and Commander D. H. Macmillan (1953), the authors state (page 206):

"Another feature of interest in these variations depends upon the curious astronomical fact that perigee does not fall back evenly around the synodic or lunar month, but 'hangs' or remains close to new moon for three or four months. It then shifts rapidly through the quarters again 'steadying up' and 'hanging' as it were at the full moon before going on past the next quarter.

"The resulting 'perigee springs' giving maximum lunar effects at syzygies (conjunction or opposition of sun and moon) consequently recur for about three months in succession during the year before they fall off in height."

In terms of the astronomical intricacies of perigean spring tides, the causal factors for this interesting circumstance are deserving of further consideration. The phenomenon in question is a function of the distribution of perturbations which is responsible for a *net* (not continuous) forward motion of perigee through successive lunar years—as well as a prolonging of the conditions responsible for perigean spring tides by a retrograde motion of perigee around the immediate time of each perigee-syzygy alignment.

These separate motions are both due to the perturbational actions of the Sun as, in its apparent motion around the ecliptic consequent upon the actual motion of the Earth, the solar body approaches an alignment in longitude with the lunar line of apsides.

As described in part II, chapter 4, in the immediate vicinity of the position of perigee-syzygy alignment these solar perturbations produce a retrograde rotation of the line of apsides of the Moon's orbit (clockwise as viewed from the north pole of the ecliptic). This retrograde motion of perigee begins about 3 days prior to the perigee-syzygy alignment and reaches a maximum angular velocity of approximately $-1.62°/^{d}$ at this position, thereafter diminishing again to zero in the following 3 days.

The physical effect of this retrograde motion of perigee (in a direction opposite to that in which the Moon is revolving around the Earth) is to cause the passage of the Moon through perigee-syzygy alignment to occur sooner, since the relative velocity between Moon and perigee is maximized at this position. Following perigee-syzygy, as both the retrograde velocity of perigee and the relative velocity between it and the Moon are diminished, a tendency exists for prolongation of the reinforcing gravitational conditions associated with perigee-syzygy which are responsible for perigean spring tides. This effect contributes to the extension of the number of days of perigean spring tides compared with ordinary spring tides.

Although, over the long term, the net motion of perigee is forward (the *mean progression of perigee*), as was seen in figures 28, 30, and 32, during any one lunar year, the net motion of perigee is direct only in certain lunar months. The net forward motion of perigee begins 1 or 2 anomalistic months prior to the time at which the Sun crosses the line of apsides, reaches a maximum angular value before the two longitudes agree, and decreases slowly to zero for 1 or 2 anomalistic months thereafter. The length of each tidal day, and the average number of days between two successive returns of the Moon to perigee, are both increased proportionately.

This is shown by the considerably higher value consistently attained in the length of any anomalistic month which brackets a date of close perigee-syzygy (see table 17). The anomalistic month is increased (as much as 1.03^{d} above its average value) by an amount considerably more than the synodic month as a result of this effect.

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The anomalistic period thus is not allowed to fall off during the months immediately preceding and following perigee-syzygy by the full 1.9760^d between the *average* lengths of the synodic and anomalistic months. (It is this greater average difference as it accumulates that destroys the commensurability between the two months, once attained.) In contrast, subject to these very small, localized differences, the lengths of the anomalistic months often remain very nearly the same at maximum value (varying only by a few digits in the second decimal place) for several successive months around the time of a close perigee-syzygy alignment.

With a near-commensurability between the synodic and anomalistic months established at such times, and partially maintained through the above circumstances, the phenomenon of perigee-syzygy alignment tends to persist. This is clearly seen among the curves of rate-of-tide-growth depicted in figs. 153–163 of chapter 8.

An additional contribution to this influence is provided by the comparatively slow apparent motion of the Sun along the ecliptic with respect to the position of perigee-syzygy. The Sun's apparent velocity along the ecliptic is only about $1^{\circ/d}$ (even less at the time of aphelion). The circumstances of a small separation-interval between perigee and syzygy, once achieved, tends to be approximately retained and extended over successive perigee-syzygy alignments.

The lengths of the anomalistic months which either contain, or closely adjoin other such months which contain instances of *ordinary perigee-syzygy* (as defined in chapter 8) are universally in excess of 28 days. Less frequently, in the case of *proxigee-syzygy*, their periods are very close to 28.5 days—equivalent to the simple average between the synodic (29.530589-day) and anomalistic (27.554551-day) months. These 28-day or larger values occur, accompanying all such close perigee-syzygy alignments, at least 1 month (and usually 2) on either side of that containing the smallest separation-interval.

This fact is confirmed in the representation of the varying lengths of both synodic and anomalistic months during a 17-year double lunar apsides cycle in table 17. The relationship between the greater lengths of the tidal days these months contain and the "windows" within which actual cases of tidal flooding often occur is also shown by the consistent pattern of 2–4 contiguous curves of extreme amplitude, each having a peak indicating an above-average rate of tide growth, among the graphs of tidal flooding potential in figs. 153–163, chapter 8.

The relative increase in gravitational force resulting from a close perigee-syzygy alignment is a direct function of the smaller separation-interval between perigee and syzygy which is, in turn, associated with a condition of more exact commensurability between the periods of the anomalistic and synodic months. It is important to note in this connection that the relationship which permits the near-coincidence of perigee and syzygy to occur is a precise intermatching of the previously noted widely varying values for the lengths of these respective months. The extreme range in length of the anomalistic months as determined from table 17 is $28.58 - 24.67$ or 3.91 days, and the corresponding extreme range of the synodic months is $29.8298 - 29.2743$ or 0.5555 day. Because of these unequal differences, the positions of perigee and syzygy only rarely attain a separation-interval of less than 6 to 6.5 minutes (e.g., 1912 January 4; 1931 March 4).

However, once a close approximation to the necessary commensurate relationship is attained and the two positions roughly coincide, they will not separate rapidly. As noted earlier, succeeding anomalistic months vary by only a few hundredths of a day around the time of closest separation between perigee and syzygy, and the variation in the corresponding maximum values of the synodic months is equally small. Thus, the existing nearly commensurable relationship is not destroyed and the separation-interval between perigee and syzygy often remains equal to, or less than ± 24 hours for 3 or 4 (and occasionally even 5) successive months (see table 16).

Declinational Influences on the Length of the Tidal Day

In the discussion of this concept of induced changes in the length of the tidal day, four different aspects of apparent lunar and solar motions as seen from the Earth are involved, all of which must be considered. These aspects are:

1. The direct reflection of the Earth's diurnal axial rotation as an apparent oppositely directed motion to the Moon and Sun on the celestial sphere.

2. A decrease in this apparent angular velocity of movement on the celestial sphere as the declination of either body increases.

3. A variation in both of the above apparent motions as the result of individual components of velocity (created by the Moon's orbital motion and the Earth's orbital motion, respectively) which the Moon and Sun possess in right ascension (i.e., directed along the celestial equator).

4. Further variations in apparent velocity introduced by (a) the inclination of the paths of individual motion of the Moon and Sun to the celestial equator, and (b) the declinations of these bodies at any given time.

The particular effects produced may be described as follows:

(a) The presence of the Moon and/or Sun on the celestial equator may, because of the Earth's fastest linear rotation in the equatorial plane, slightly decrease the time during which their forces can act. A celestial object located over the Equator and lacking any motion of its own would exhibit its greatest possible apparent angular velocity across the sky. This is because the apparent motion of any body in this position reflects the total velocity component of the rotating Earth transferred to an opposite direction. The period of time between the rising and setting of such objects is, therefore, the least, their apparent movement in a westward direction across the sky is the most rapid, and the angular distance covered in right ascension at the end of the day is the smallest.

The apparent westward movement of the Moon due to the Earth's diurnal rotation is directly opposite to the actual eastward movement pursued by that body in its own orbital motion. Similarly, in the case of the Sun, its apparent diurnal motion is opposite to the apparent eastward motion produced as a result of the revolutionary motion of the Earth in its orbit. The westwardly directed diurnal motion of either of these two bodies must, therefore, be subtracted from their respective eastward motions, a fact which, by decreasing the eastward motion, tends to decrease the length of the tidal day.

When the apparent diurnal motion of the object is the greatest, as it is when located on the celestial equator, the magnitude of the component to be subtracted from the eastward angular motion—a motion which, by itself, lengthens the tidal day—is the greatest, and the tidal day is consequently lengthened by the least amount.

This principle is also applicable to the Moon's own apparent orbital motion which—after subtracting the Earth's full rotational velocity—also is the least in right ascension when the Moon is on or near the celestial equator. However, the maximum velocity of the Moon's real motion in orbit at times of perigee-syzygy varies between successive anomalistic months, being greatest at times of close perigee-syzygy alignments. With this larger velocity vector of direct motion, the length of the tidal day is diminished the least from the foregoing cause at such times of perigee-syzygy.

(b) As either the Sun or Moon moves northerly or southerly in declination subject to its own apparent orbital motion, its apparent westward (diurnal) velocity decreases and hence the velocity component to be subtracted from its eastward motion is less. The net value of the eastward motion accordingly remains larger. The tidal day is lengthened in proportion.

(c) Furthermore, as described earlier, at the summer and winter solstices where the instantaneous change in the declinational motion of the Sun becomes zero, the Sun's entire annual motion is eastward in right ascension, and the tidal day is lengthened the most from the Sun's influence. The same holds true for the Moon, twice each tropical month, as the influence of its eastward motion in lengthening the tidal day becomes the greatest near the crests and troughs of the curves representing the Moon's monthly motion in declination. (See figs. 44–45.)

(d) The conditions of maximum lunar declination necessary to achieve certain favorable declinational alignments between Sun and Moon and consequent enhanced tide-raising forces, as noted on page 196, are also favorable in terms of lengthening the tidal day. Accordingly, as the result of these combined factors, it is often found that, where anomalistic and semidiurnal tides are prominent, as on the east coast of Canada and the northeast coast of the United States, the coincidence of perigean spring tides with these high-declination circumstances for both the Moon and Sun—plus strong onshore winds—is often sufficient to produce extensive tidal flooding. The number of instances of this type in table 1 is statistically large, indicating that the position of the Moon on the Equator is not an overriding determinant for the production of extraordinarily high tides and tidal flooding (cf., p. 112, col. 2, final par.).

(e) In this same regard, one other phenomenon may provide a significant contribution to the lengthening of the tidal day at the points of greatest declination in the motions of the Moon. This is the nodical cycle (page 193) which, once in each 18.6-year period, brings the Moon to its maximum possible declination ($\pm 28.5°$) with respect to the celestial equator.

It has been seen (pp. 132–135) that the greater is the value of the declination at the peaks and troughs of the declination curve, the larger is the motion in right ascension at that time. Thus, the 18.6-year nodical cycle provides another circumstance wherein, with the lunar declination at its maximum possible value, and with the motion in right ascension correspondingly augmented, the tidal day is also lengthened in proportional amount.

(f) As derived mathematically on pages 186–189 and illustrated in figs. 165a, b, the rate of tidal growth, which is a direct measure of the strength of the tidal forces acting, must also be corrected by a term $\cos^2 \delta$ to include the effects of the Moon's variation in declination.

The Effect of the Lunar Apsides Cycle

By abstracting, as has been done in table 18, a series of values representing the changing individual lengths of the synodic months, an interesting relationship is revealed involving: (1) the perturbational effect of the Sun upon the major axis of the lunar orbit at the times of perigee-syzygy; (2) the increased gravitational attraction of the Sun on the Moon's orbit at perihelion; (3) the synodic period of the Moon's revolution; and (4) the lunar apsides cycle of 8.849 tropical years (3,232 mean solar days).[e] The latter cycle is the period of time required for one complete rotation of the lunar line of apsides through 360° of longitude at its mean rate of 0.111404°/day, subject to the perturbational action of the Sun.

The relationship in question is basically one deriving from the previously mentioned *annual equation* (see p. 165), further augmented by the coincidence of perigee-syzygy. When various maximum lengths of the synodic months created by the alignment of perigee and syzygy are taken from table 17 and are retabulated over an extended interval of time, a definite periodicity in these values is noted. The synodic months vary through successive maxima and minima approximately 4.4 years apart, returning to the same phase again in just less than 9 years.

[e] This is the value adopted by the International Astronomical Union as part of the IAU System of Astronomical Constants. The mean motion of apogee and perigee (although not its irregularities) in a forward direction at approximately 3°/anomalistic month was known to Hipparchus as early as the second century, B.C. Sir Isaac Newton discusses the theory of the progression of the line of apsides in Book I, Proposition 66, Theorem 26, Corollary VII of his *Principia,* but gives neither the mean motion nor period. In his monumental work, *Manual of Tides,* 1894–1907 (part I, page 491), Rollin A. Harris tabulates the value of 3,232.591040 days. Other modern sources agree with the value of 8.849 tropical (in place of either Julian or Gregorian) years. The figure 9½ years quoted on page 356 of Forest Ray Moulton's classic work *Celestial Mechanics* is obviously a misprint.

Modification of the Lunar Period by the Lunar Apsides Cycle

In considering the relevant factors which act to alter the period of revolution of the Moon, reference can be made to the equation cited in the foregoing section, expressing the effect of perturbations on the lunar orbital motion, namely:

$$P_{☾}=\frac{2\pi a_{☾}^{3/2}}{k(M_{\oplus}+m_{☾})^{1/2}}$$

Although $P_{☾}$ in this equation represents the sidereal period of the Moon, it may easily be converted to the synodic period of revolution without introducing further significant variables, as later shown. It is obvious from the above equation that, since all other factors are constants, the period varies only as a [f], the semimajor axis of the lunar orbit. It is also apparent from the auxiliary equation on page 173 that, since the rate of change of a varies directly with its own value and with $V_{☾}$, the Moon's orbital velocity, the effect of the Sun's tangential force in altering a is increased the most at perigee-syzygy, when the Moon's angular velocity is the greatest. Also, when a becomes larger, its rate of increase grows larger.

TABLE 18.—*Variation in Length of the Synodic Month, Within the 8.849/Year Lunar Apsides Cycle*

Dates	Maximum length of synodic month (days)
1959 November–December	29. 7965
1960–61 December–January	29. 7785
1961 January–January	[1] 29. 8201
1962 January–February	29. 7924
1963 March–April	29. 7139
1964 May–June	29. 6528
1965 July–August	[2] 29. 6477
1966 September–October	29. 7174
1967 October–November	29. 7792
1968 December–January	29. 8055
1969–70 December–January	29. 8056
1970 January–February	[1] 29. 8076
1971 February–March	29. 7861
1972 February–March	29. 7035
1973 May–June	29. 6507
1974 August–September	[2] 29. 6444
1975 October–November	29. 7236

[1] Largest maximum.
[2] Smallest maximum.

[f] More exactly, $P^2 \propto a^3$.

The variable magnitude, of **T**, the tangential force of the Sun on the lunar orbit, depends upon the distance of the Moon from the Sun, which is a function of its position in orbit, and the relative orientations of the elliptical orbits of the Earth and Moon with respect to the Sun. (All cases represented in this list involve the Moon at a position of perigee-syzygy. Hence, no case of an absolute solar perigee can be included, since the latter situation requires the coincidence of apogee-syzygy with the Earth at perihelion.)

It will be observed that the difference, in years, between the two largest maxima in table 18 agrees very closely with the period of rotation of the line of apsides through 360° in 8.849 tropical years—the only full lunar cycle of this magnitude. The rotation of the lunar apsides through one-half of this cycle in 4.424 years produces the two different alignments of the lunar orbit shown in fig. 42. This period also very closely matches the interval between the largest and smallest maxima in the table.

Positioning the perigee-syzygy situation of 1961 January 16 (occurring within the longest synodic month in this 17-year series) at (1) as shown in figure 42, the perigee-syzygy of 1965 July 29 (occurring within the shortest synodic month) almost exactly occupies position (2). As shown in this figure, the Moon in position (1) is approximately 3 million miles nearer to the Sun than is position (2). This positioning alignment can be repeated for the extreme maximum value of the synodic month accompanying the perigee-syzygy situation of 1970 January 8, and the smallest maximum value related to the perigee-syzygy of 1974 August 17.

Both the positions (1) and (2) will experience a lengthening of the major axis (and hence the semimajor axis)

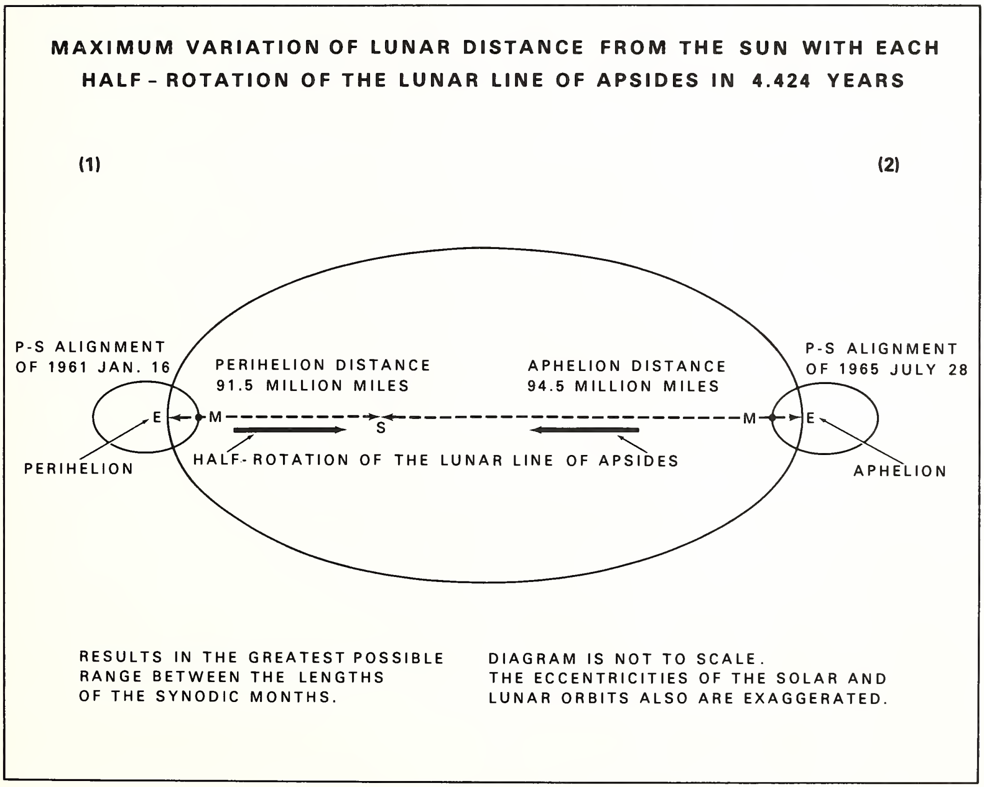


FIGURE 42.—(Discussed in text.)

TABLE OF USUAL HARMONIC

TYPE	SYMBOL	ORIGIN & NAME	ARGUMENT: V_0	+ u	HARMONIC NOTATION OF THE TIDAL INSTITUTE OF LIVERPOOL (Coefficients (each augmented by 5) are arranged in the following order. $\tau+s+h.\ p+N'+p_1$ argument… component… group… type…)	NATURE	ANGULAR SPEED PER MEAN SOLAR HOUR: FORMULA	OTHER FORMULA	VALUE
SEMI-DIURNAL	M_2	☾ principal	$2t+2h-2s$	$2\xi-2\nu$	255 - (555)	$[K_1+O_1]$	$2\theta+2\eta-2\sigma$	$2(\gamma-\sigma)$	28°. 984 104 2
	N_2	larger elliptic	$2t+2h-3s+p$	$2\xi-2\nu$	245 - (855)		$2\theta+2\eta-3\sigma+\omega$	$2(\gamma-\sigma)-(\sigma-\bar{\omega})$	28°. 439 729 5
	L_2	smaller »	$2t+2h-s-p+180°$	$2\xi-2\nu-(R)$	285 - (455)	$[M_4-N_2]$	$2\theta+2\eta-\sigma-\bar{\omega}$	$2(\gamma-\sigma)+(\sigma-\bar{\omega})$	29°. 528 478 8
	$2N$	2nd order »	$2t+2h-4s+2p$	$2\xi-2\nu$	235 - (755)		$2\theta+2\eta-4\sigma+2\bar{\omega}$	$2(\gamma-\sigma)-2(\sigma-\bar{\omega})$	27°. 895 354 8
	ν_2	larger evectional	$2t+4h-3s-p$	$2\xi-2\nu$	247 - (455)		$2\theta+4\eta-3\sigma-\bar{\omega}$	$2(\gamma-\sigma)-(\sigma-2\eta)-\bar{\omega}$	28°. 512 583 1
	λ_2	smaller »	$2t-s+p+180°$	$2\xi-2\nu$	263 - (655)		$2\theta-\sigma+\bar{\omega}$	$2(\gamma-\sigma)-(\sigma-2\eta)+\bar{\omega}$	29°. 455 625 3
	μ_2	variational	$2t+4h-4s$	$2\xi-2\nu$	237 - (555)		$2\theta+4\eta-4\sigma$	$2(\gamma-\sigma)-2(\sigma-\eta)$	27°. 968 208 4
	S_2	⊙ principal	$[S_1]\times 2$	Zéro	273 - (555)		$[S_1]\times 2$		30°.
	T_2	larger elliptic	$2t-h+p$	»	272 - (558)		$2\theta-\eta+\bar{\omega}_1$	$2(\gamma-\eta)-\eta$	29°. 958 933 3
	R_2	smaller »	$2t+h-p_1+180°$	»	274 - (554)		$2\theta+\eta-\bar{\omega}_1$	$2(\gamma-\eta)+\eta$	30°. 041 066 7
	K_2	☾ ⊙ declinational	$2t+2h$	$-2\nu''$	275 - (555)		$2\theta+2\eta$	2γ	30°. 082 137 3
	U_2								
DIURNAL	O_1	☾ principal declinational	$t+h-2s+90°$	$2\xi-\nu$	145 - (555)	$[M_2-K_1]$	$\theta+\eta-2\sigma$	$\gamma-2\sigma$	13°. 943 035 8
	OO	2nd order	$t+h+2s-90°$	$-2\xi-\nu$	165 - (555)		$\theta+\eta+2\sigma$	$\gamma+2\sigma$	16°. 139 101 7
	Q_1	larger elliptic	$t+h-3s+p+90°$	$2\xi-\nu$	135 - (855)	$[N_2-K_1]$	$\theta+\eta-3\sigma+\bar{\omega}$	$\gamma-2\sigma-(\sigma-\bar{\omega})$	13°. 398 660 9
	M_1	smaller »	$\left\{\begin{matrix}t+h-s+p\\ t+h-s\end{matrix}\right\}-90°$	$\left\{\begin{matrix}-\nu-(Qu)\\ \xi-\nu+(Q)\end{matrix}\right.$	155 - (855) (555)	$[N_2-O_1]$	$\theta+\eta-\sigma+\bar{\omega}$	$\gamma-(\sigma-\bar{\omega})$	14°. 498 893 9
	J_1	smaller elliptic	$t+h+s-p-90°$	$-\nu$	175 - (455)		$\theta+\eta+\sigma-\bar{\omega}$	$\gamma+\sigma-\omega$	15°. 585 443 3
	$2Q_1$	2nd order »	$t+h-4s+2p+90°$	$2\xi-\nu$	125 - (755)		$\theta+\eta-4\sigma+2\bar{\omega}$	$\gamma-2\sigma-2(\sigma-\bar{\omega})$	12°. 854 288 2
	ρ_1	larger evectional	$t+3h-3s-p+90°$	$2\xi-\nu$	137 - (455)		$\theta+3\eta-3\sigma-\bar{\omega}$	$\gamma-2\sigma-(\sigma-2\eta)-\bar{\omega}$	13°. 471 514 5
	σ_1	variational			[127 - (555)]		$\theta+3\eta-4\sigma$	$\gamma+2\eta-4\sigma$	
	P_1	○ principal declinational	$t-h+90°$		163 - (555)	$[S_2-K_1]$	$\theta-\eta$	$\gamma-2\eta$	14°. 958 931 4
	K_1	☾⊙ declinational	$t+h-90°$	$-\nu'$	165 - (555)	$[M_2-O_1]$	$\theta+\eta$	γ	15°. 041 068 6
	S_1	Meteorological (land and sea breeze)	t	Zéro	164 - (....)		θ	$\gamma-\eta$	15°.
TER-DIURNAL	M_3	☾ (from 4th power of parallax)			355 - (555)	$[\frac{1}{2}M_2]\times 3$			(43°.478 158 3).
OVER TIDES	M_4	☾ quarter-diurnal				$[\frac{1}{2}M_2]\times 4$			(57°. 968 208 4)
	M_6	sixth-diurnal				$\times 8$			(88°. 952 312 7)
	M_8	eighth-diurnal				$\times 8$			(115°. 936 415 9)
	S_3	⊙ ter-diurnal				$[S_1]\ \times 3$			(45°.)
	S_4	qnarter-diurnal				$\times 4$			(60°.)
	S_6	sixth-diurnal				$\times 8$			(90°.)
	S_8	eighth-diurnal				$\times 8$			(120°.)
COMPOUND TIDES	MS ou $(MS)_4$	quarter-diurnal				$[M_2+S_2]$			(58°. 984 104 2)
	$2MS$ ou μ_2	semi-diurnal			237 - (555)	$[M_4-S_2]$			(27°. 968 208 4)
	$3MS$					$[M_3-S_2]$			(13°. 476 158 3)
	$2MS_6$	sixth-diurnal				$[M_4+S_2]$			(87°. 968 208 4)
	$MN = (MN)_4$	quarter-diurnal				$[M_2+N_2]$			(57°. 423 833 7)
	$2MN_6$	sixth-diurnal				$[M_4+N_2]$			(73°. 887 320 7)
	$(MK)_3$	ter-diurnal			365 - (455)	$[M_2+K_1]$	$[M_4-O_1]$		(44°. 025 172 9)
	$(2MK)_3$	ter-diurnal			345 - (655)	$[M_4-K_1]$	$[M_2+O_1]$		(42°. 927 139 8)
	$(2SM)_2$	semi-diurnal				$[S_4-M_2]$			(31°. 015 895 8)
	$3SM$	diurnal				$[S_3-M_2]$			(18°. 015 895 8)
	SO_1	diurnal			183 - (555)	$[S_2-O_1]$			(18°. 058 964 4)
	$(SK)_3$	ter-diurnal				$[S_2+K_1]$			(45°. 041 068 8)
LONG PERIOD	Mf	☾ fortnightly	$2s$	-2ξ	075 - (555)	$[K_1-O\ ]$	2σ		1°. 098 033 1
	MSf	☾⊙ fortnightly synodic variational			073 - (555)	$[S_2-M_2]$			(1°. 015 895 8)
	Mm	☾ monthly	$s-p$	Zéro	085 - (455)	$[M_2-N_2]$	$\sigma-\bar{\omega}$		0°. 544 374 7
	Ssa	⊙ semi-annual			057 - (555)	$[Sa]\times 2$			(0°. 082 137 3)
	Sa	⊙ meteorological annual (monsoon)	h	Zéro	058 - (.....)		η		0°. 041 068 8

ASTRONOMIC ELEMENTS FOR THE ARGUMENT

- t hour angle of mean ⊙ (mean time).
- $\tau = t^\circ + h - s - L$.
- h mean longitude of ⊙.
- s mean longitude of ☾.
- p d° d° of perigee ☾.
- p_1 d° d° of perigee ⊙.
- $-N' = N$ d° d° of ascending node Ω.
- ξ d° d° of intersection (reckoned on the ☾ orbit).
- ν right ascension of intersection.
- $\nu' = f(\nu, I)$.
- $\nu'' = f(\nu, I)$.
- I inclination of ☾ orbit on Equator.
- L local longitude West of Greenwich.

SPEED OF CHANGE	PER MEAN HOUR	PER MEAN DAY
γ angular speed of Earth's rotation.	15° 041 088 8	
$\theta = \gamma - \eta$.	15°	
$\dot{\tau} = \theta + \eta - \sigma$	....	360° – 12° 190 749 39
η mean movement of ⊙.	0° 041 088 6	0° 985 647 34
σ mean movement of ☾.	0° 549 018 5	13° 178 398 73
$\bar{\omega}$ d° d° of perigee ☾.	0° 004 641 8	0° 111 404 08
$\bar{\omega}_1$ d° d° of perigee ⊙.	0° 000 002 0	0° 000 047 07
$\dot{N}'$	....	0° 052 953 92

FIGURE 43.—This table is reduced from a much larger chart appearing as a foldout in *Tide Predicting Machines*, Special reference source on the development of analytic constituents pertaining to the harmonic analysis of the tides.

COMPONENTS OF THE TIDE

MEAN VALUE OF CŒFFICIENT		PERIOD	COMPONENTS AS GIVEN BY THE MACHINES													
			British Association or Tide Predictor N° 1	Roberts or India Office Br. Tide-Predictor N° 2		Thomson Br. Tide-Predictor N° 3	Now in France	Ferrel Machine or U. S. Tide Predicting Machine N° 1 for maxima and minima	Roberts Universal Tide Predictor Br. N° 4	U. S. Coast & Geodetic Survey Tide-Predicting Machine N° 2	Brazilian Machine (Kelvin) N° 5	Kelvin Machine of Japan N° 6	German Machine	Kelvin Pronosticador Argentine	2 Kelvin Machines Japan	Kelvin Machine Portugal	Kelvin Machine Tidal Institute Liverpool
0.4543	M_2	12^h42060	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2	M_2
0.0871	N_2	12 85835	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2	N_2
0.0128	L_2	12 19182	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2	L_2
0.0117	$2N$	12 8783			$2N$				$2N$	$2N$							$2N_2$
0.0123 à 0.0171	ν_2	12 82601		ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2	ν_2
0.0033 à 0.0074	λ_2	12 22177		λ_2	(supp.)	—	—	λ_2	λ_2	λ_2			λ_2				
0.0074 à 0.0109	μ_2	12 87188		μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2	μ_2
0.2120	S_2	12 hours	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2	S_2
0.0124	T_2	12 01645			T_2		T_2	T_2	T_2	T_2							T_2
0.0018	R_2	11 98359								R_2							
0.0575 { 0,0393 0,0182	K_2	11 96724	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2	K_2
	U_2							U_2									
0.1888	O_1	25^h81935		O_1	O_1	O_1	O_1	O_1	O_1	O_1	O_1	O	O_1	O	O_1	O_1	O_1
0.0081	OO	22 308								OO							
0.0385	Q_1	28 86836	Q_1	Q_1	Q_1	Q_1	Q_1	Q_1	Q_1	Q_1	Q_1	Q	Q_1	Q	Q_1	Q_1	Q_1
0.0149	M_1	24 84120						M_1		M_1							
0.0149	J_1	23 09847		J_1	J_1				J_1	J_1			J_1				J_1
0.0049	$2Q$	28 006								$2Q$							
0.0051 à 0.0071	ρ_1	28 723								ρ_1							
	σ_1																
0.0878	P_1	24 06589	P_1	P_1	P_1	P_1	P_1	P	P_1	P_1	P_1	P_1.	P_1	P_1	P_1	P_1	P_1
0.2654 { 0.1812 0.0842	K_1	23 93447	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1	K_1
....	S_1	24 hours		S_1	S_1	S_1	S_1		S_1	S_1	S_1			S_1		S_1	S_1
0.0060	M_3	8^h2804							M_3	M_3							M_3
	M_4	6^h2103	M_4	M_4	M_4	M_4	M_4	M_4	M_4	M_4		M_4	M_4	M_4	M_4	M_4	M_4
	M_6	4 1402		M_6	M_6	M_6	M_6	M_6	M_6	M_6			M_6				M_6
	M_8	3 1052							M_8	M_8							
	S_3	8 hours															
	S_4	6 hours							S_4	S_4			S_4				S_4
	S_6	4 hours								S_6							
	S_8	3 hours															
petits fonds	MS_4	6^h1033	MS_4	MS_4	MS_4	MS_4	MS_4	MS_4	MS_4	MS_4		MS_4	MS_4	MS_4	MS_4	MS_4	MS_4
	$2MS$	12 8718															
	$3MS$								$3MS$								
	$2MS_6$																$2MS_6$
	MN	8 2693			MN				MN	MN			MN_4				MN_4
	$2MN_6$																$2MN_6$
	MK_3	8 1772			MK				MK	MK							MK_3
	$2MK_3$	8 3863			$2MK$				$2MK$	$2MK$							$2MK_3$
	$2SM_2$	11 6070		$2SM$	$2SM$				$2SM$	$2SM$			$2SM$				$2SM_2$
	$3SM$								$3SM$								
	SO_1	22 420											SO_1				
0.0783	Mf	13 j. 777							Mf	Mf							
0.0042	MSf	14 785							MSf	MSf							
0.0414	Mm	27 555							Mm	Mm							
0.0385	Ssa	182 821		Ssa	Ssa				Ssa	Ssa		Ssa		Ssa	Ssa	Ssa	
....	Sa	365 242		Sa	Sa			Sa	Sa	Sa		Sa		Sa	Sa	Sa	
TOTAL NUMBER OF COMPONENTS			10	20	24	15	16	19	33 + 7 disp.	37	12	15	20	18	15	18	26 + 3 disp.
DATE OF CONSTRUCTION			1872-1873	1879	modif. 1891	1881	1901 modif.	1882	1908	1894-1910	1910	1914	1915-1916	1918 1920 modif.	1924	1924	1924-25
SERVICE			*Has been used but little. Mr. Roberts used it for tracing curves exhibited with the apparatus at the Exhibition of Paris 1878.*	*Under the charge of Mr. E. Roberts. Provided predictions for Bombay and Karachi in 1880, and for 8 Indian ports in 1881. Afterwards for 37 Indian & Oriental ports in British possessions Aden 1903. Siam 1916. Brisbane 1923. New Zealand. Predictions for Indian Tide Tables.*		*Used for Lord Kelvin's experiments.*	*Tide predictions for French Colonies of Atlantic Ocean, Indian Ocean, and China Seas Hourly predictions for the Coasts of France, St-Malo and Brest.*	*Tide Tables published by the U.S. Coast & Geodetic Survey from 1885 to 1911.*	*Tide predictions are carried out for British Admiralty, for Indian Survey Department, and for 12 ports of Canado, for the Canadian Government.*	*Has been used since 1912 for compiling the greater part of the Tide Tables, issued by the U.S. Coast & Geodetic Survey (61 ports of reference). Is also used for predictions for New South Wales & Western Australia.*	*Predictions for "Annuaro publicado pelo Observatorio Nacional do Ria de Janeiro"*	*Used for predictions for Yokoska, Sasebo Shimonosaki & Zinsen.*	*Predictions for German Tide Table for Le Haore, Cherbourg, Brest, Dover, Liverpool, Capetown, Aden, Bomboy, Dublat, Rangoon, Singapore, Hongkong, Woosung, Sasebo, Yokosuka, Sydney, Balboa, Valparaiso, Buenos-Aires & Ria de Janeiro.*	*Used since 1920 for preparing Tablas de Marea of the Argentine Republic (12 ports of reference).*	*Have been used for comparative tests of machines by the Tidal Institute of Liverpool.*	*Has been studied and tested by the Tidal Institute of Liverpool.*	*Predictions for the Admiralty since 1924 for 7 ports of Australia and New Zealand and for 3 ports of Japan. Detailed predictions for Liverpool and Portland for Holden's and Admiralty's Tables. Predictions for the Canadian Tidal Survey.*
SITUATION			*Removed in 1876 to the South Kensington Museum.*	*At the Natural Physical Laboratory Teddington from 1903 then removed to Dehra-Dun (Survey of India).*		*At Messrs. Kelvin & James White, Glasgow till 1901.*	*At the Service Hydrographique Paris, from 1901.*	*U. S. Coast & Geodetic Survey, Washington.*	*At Edward Roberts & Son Broadstairs England.*	*U.S. Coast & Geodetic Survey Office, Washington.*	*Rio de Janeiro, Observatorio Nacional.*	*Hydrographic Office, Tokyo.*	*Deutsche zeewarte, Hamburg from 1919.*	*Argentine Hydrographic Office, Buenos Aires*	*Japanese Hydrographic Office. Tokyo.*	*Portuguese Hydrographic Office. Lisbon.*	*Bidston Observatory.*

Publication No. 13, International Hydrographic Bureau, July 1926. It is of considerable significance as an historical of the lunar orbit as the Moon reaches perigee-syzygy. However, because of the smaller distance and greater gravitational attraction of the Sun at (1), the increase in *a* will be greater at (1) than at (2). This increase in *a* produces a corresponding increase in the value of $P_{☽}$ or M_{sid}, the length of the sidereal month, from which the length of the synodic month may be obtained using the equation:

$$\frac{1}{M_{sid}}=\frac{1}{M_{syn}}-\frac{1}{Y_{sid}}$$

where

M_{syn} = the length of the synodic month
M_{sid} = the length of the sidereal month
Y_{sid} = the length of the sidereal year

Other Time-Related Factors Susceptible to Analysis by the Methods of Harmonic Analysis

As an addendum to the main topic of this chapter, and a necessary forerunner to certain discussions in chapter 8, several additional factors relating to the variable of time as it affects the tides must be mentioned. These factors—rather than prolong the overall period of maximum force application as in the preceding examples—most commonly delay the exact time of occurrence of the observed effects of the tide-raising forces. (Although possible worldwide, only a few cases of marked *acceleration* of tide arrival times occur in North American waters.) The result is that both the high and low waters may occur at a time considerably after those at which the Moon crosses the local meridian, or reaches either its perigee or syzygy positions.

One cause of delay in the arrival of high water following the meridian passage of the Moon is the inertial response of the vast mass of tidal waters set in motion. This response is, in turn, locally affected by the combined hydrodynamic, hydraulic, and hydrographic characteristics (including the free period of oscillation and dynamic resonance) of the particular ocean basin or portions thereof in which the waters are situated. Other modifications in the arrival times of the tidal maxima and minima are a function of physical, oceanographic, geographic, and astronomical parameters.

Two such influences exist which are directly related to the astronomical configurations responsible for the production of perigean spring tides and, therefore, are causally connected with the exact time of their occurrence. These are the *phase age* and *parallax age*. Singly, they produce a delay in the response of the ocean waters to the augmented force factors created respectively by: (1) the direct alignment of Moon and Sun at conjunction and opposition; and (2) the larger parallax and closer distance of the Moon to the Earth at the time of perigee.

Because both of these effects are of dynamic origin, they may be described most expediently by resorting to an analytic procedure employing the appropriate harmonic constants of the tides. The rigorous methods of application of these constants are fully explained in *Manual of Harmonic Analysis and Prediction of Tides* (Washington, D.C., U.S. Government Printing Office, rev. (1940) ed. (1941) and the British *Admiralty Manual of Tides* (His Majesty's Stationery Office, London, 1941) and will not be repeated here, except for a brief résumé of the basic tidal constituents involved. (See fig. 43.)

Evaluation of the Principal Harmonic Constituents

According to the methodology of harmonic analysis, the composite of lunar and solar forces interacting to produce the tides and the resulting rise and fall of the tidal waters are dealt with as a system of interrelated harmonic constituents, susceptible to integrated mathematical solution. The actual tides are treated as if they were made up of a series of idealized, mathematically expressible component tides. The end products of this analysis are tide height and arrival time.

In the computational process, the tidal amplitudes and arrival times are represented by a series of cyclical expressions containing both variable terms and constant coefficients which allow for a discrete application of the solutions to individual tidal stations. It must be pointed out that these so-called constants also vary over the years, as the result of both astronomical and hydrographic factors. In the latter case, repeated series of observations at local stations, obtained and evaluated over successive 19-year Metonic cycles, make it possible to apply empirical adjustments and corrections.

The two most important of these constants are those which represent the tidal forces reaching a maximum twice in each lunar and solar day. They are a direct function of the rotation of the Earth and the changing motions, gravitational attractions, and phase interrelationships of the Moon and Sun during the different periods in which these two bodies pass successively through upper and lower meridian transit. The corresponding lunar and solar components contributing their effects to tidal amplitudes are designated (in units of feet or meters) by M_2 and S_2, and are known as the *principal semidiurnal lunar* and *principal semidiurnal solar* constituents, respectively.

A very interesting relationship exists between these two numerical constants and the phase interrelationships of the Moon and Sun at syzygy and at quadrature, from which, with a knowledge of the established tidal range at any station, both constants can be approximately evaluated. If the mean spring range and mean neap range are determined at any tide station over a minimum 19-year Metonic cycle, these constants are directly calculable.

For example, such continuous series of measurements reveal that at Sandy Hook (New York Harbor), N.J., the mean range of *high water springs* (the average of many years of observation of spring tide levels) is $\bar{R}=5.6$ feet. Similarly, the value for the mean range of *high water neap* tides (those produced successively at lunar quadratures) is $\bar{R}_N=3.7$ feet.

Since the first value is the result of the vector sum of the forces of the Moon and Sun aligned at either new or full moon and the second results from the gravitational force of the Sun counteracting (at right angles) that of the Moon, their combined forces (neglecting all other tide-altering functions) may be expressed algebraically as

$$2\ (M_2+S_2)=\bar{R}_S$$
$$2\ (M_2-S_2)=\bar{R}_N$$

whence

$$2\ M_2+2S_2=\bar{R}_S$$
$$2\ M_2-2S_2=\bar{R}_N$$
$$4\ M_2=\bar{R}_S+\bar{R}_N$$

from which, inserting the values for $\bar{R}_S$ and $\bar{R}_N$, the value of M_2 can be determined and, by substitution of this value in either of the original equations, S_2 also may be obtained.

Since these values are here computed independently of any other harmonic constituents, they are only approximate, but sufficiently representative to reveal much concerning the nature of the local tides.

Despite the frequent previous references to high tides associated with a meridian transit of the Moon, one very important tidal characteristic easily observed at any station is the almost universal difference between the time a meridian transit of the Moon occurs and the actual arrival of high water.

Since the Moon is the predominant tide-raising body, two additional constants can be used to indicate the theoretical interval in time or angle following the meridian transit of the Moon at which the next following high water occurs. The tidal constituent known as the *epoch* or *phase lag* of M (not to be confused with the *age of the phase inequality* later to be discussed) designated symbolically as M_2°—when divided by two and converted from degrees of arc to hours of time—roughly approximates this lunitidal delay factor.

However, empirical data based upon repeated tide observations provide far more accurate results. Many years of measurements at a given tide station serve to establish the so-called *mean high-water lunitidal interval,* which is the average value of the difference in time between the meridian transit of the true Moon (all phases) and the next succeeding high tide. An actual example will illustrate the primary tide-raising influence of the Moon.

Since the period of P of M_2° is 12.42060^h, and the mean high-water lunitidal interval (HWI) at Sandy Hook, N.J., as computed from many years of observations is 7^h38^m, converting these two values into arc measurement, the value of M_2° may be computed approximately from the relationship:

$$M_2^\circ=\frac{360°\times HWI°}{P°}=\frac{360°\times 0.509°}{0.828°}=221°$$

A more accurate empirically derived value of M_2° for this location is 222°.

By direct analogy, the *principal semidiurnal solar constituent* of the tide is expressed by the terms S_2, referring to its amplitude, and S_2°, its epoch.

The Phase Age and Parallax Age

The production of ordinary spring tides is dependent upon the combined gravitational attraction of the Moon and Sun as both bodies are aligned at either new moon or full moon. Hence, with the occurrence of syzygy, the delay in time between meridian passage of the Moon and arrival of the correspondingly amplified high tide is known as the *age of the phase inequality.* It is represented at any location approximately by the difference between the respective epochs of the principal semidiurnal solar and lunar constants for that location. More exactly, expressing the age of the phase inequality by ϕ:

$$\phi\ \text{(in hours)} = 0.984\ (S_2^\circ - M_2^\circ)\ \text{(in degrees)}$$

That is, the greater is the influence of the Sun on the local tidal waters, tending to detract from the principal effect of the Moon, the greater is the value of ϕ.

It is important to mention at this point that this particular syzygy influence of the Sun should not be confused with another solar gravitational influence occurring at any position in the lunar orbit in connection with the phenomena of tidal priming and lagging. Both of these phenomena are discussed in chapter 8.

In the same manner, the augmentation in the range of the tides produced by the passage of the Moon through perigee does not occur exactly at the time of lunar transit across the local meridian of a place. A similar lag known as the *age of parallax inequality* is involved. This delay factor may likewise be computed from the harmonic constants for any location.

Two appropriate lunar constants dependent upon the anomalistic period in which the Moon revolves from perigee to perigee are indicated by N_2 and N_2°, and are termed the *larger lunar-elliptic semidiurnal* constituents. Because the parallax effect resulting from the Moon's passage through perigee (represented in phase relation by N_2°) is superimposed upon the principal semidiurnal lunar effect (represented correspondingly by M_2°), their approximate resultant may be obtained by subtracting the one from the other. Representing by χ the *parallax age,* or interval between meridian passage of perigee and the production of an augmented high tide near the time of perigee:

$$\chi \text{ (in hours)} = 1.837\ (M_2^\circ - N_2^\circ)\ \text{(in degrees)}$$

Since it is possible for N_2° to exceed M_2° (e.g., in parts of the Gulf of Mexico), occasionally the result is negative, and the perigean tides *precede* the meridian passage of the Moon.

As examples of the preceding two phenomena, the phase age at Sandy Hook, N.J., is 0.984 $(S_2^\circ - M_2^\circ) =$ 0.984 (244°—222°=+22^h, and the parallax age is 1.837 $(M_2^\circ - N_2^\circ)$ = 1.837 (222°−204°) = +33^h. In the case of a meridian passage of (1) a new or full moon, or (2) the position of perigee, these are the theoretical intervals of time after which one would expect to find the arrival of augmented high tides associated with syzygy or perigee, respectively.

When the two phenomena, syzygy and perigee, occur together, the delay in the resulting tides of increased range following the time of lunar transit is noncumulative but agrees approximately with the average of these two effects.

Variation in Tidal Range, and in the Types of Tides

An indication of the relative *heights* of the water levels produced at times of perigee-syzygy is given by the following rule-of-thumb analysis:

The ordinary spring tide, produced at time of new moon or full moon (i.e., syzygy) alone, can add approximately 20% to the range of the tides above the mean spring range.

The passage of the Moon through perigee (creating perigean tides) can also, by itself, increase the range of the tides by approximately 20% above the mean spring range.

In the combination of these two phenomena at times of perigee-syzygy, the daily range of the tides is increased nearly as the sum of the two, or 40% above the mean spring range. However, a considerable number of other factors, to be discussed in chapters 7 and 8, can alter this value, and it should be regarded only as a representative figure.

Before entering into the discussions of chapter 8 it is logical in the present connection to indicate that two other constants, diurnal in nature, are used to define the declinational effects of the Moon on the tides (including the diurnal inequality). These are designated as K_1 and O_1 (representing the *lunisolar declinational* and *principal declinational* constituents, respectively). The production of the maximum range in the tides resulting from the effects of diurnal inequality undergoes a similar delay following the local transit of the Moon which is known as the *age of the diurnal inequality* and, if symbolized by Δ, is expressed in the relationship:

$$\Delta \text{ (in hours)} = 0.911\ (K_1^\circ - O_1^\circ)\ \text{(in degrees)}$$

Significantly, in conjunction with the harmonic constant M representing the principal lunar semidiurnal constituent of the tides, these two constants also may be used to isolate and identify the particular type of tide common to any one oceanographic province.

As shown in figure 6 of the appendix, tides in which the diurnal components (represented principally by the tide-raising influence of the Sun) predominate are described as *diurnal tides.* Those in which the influence of the semidiurnal constituent due to the Sun (S_2) and semidiurnal constituent due to the Moon (M_2) are approximately equally felt are described as *mixed tides.* Finally, those in which the semidiurnal constituent of the Moon (M_2) predominates are termed *semidiurnal tides.*

A quantitative method of classifying local tides into one of these three types is available from the relationships given in table 19.

TABLE 19.—*Types of Tides (With Index and Range) at Various Locations Along the Atlantic, Pacific, and Gulf Coasts of North America*

Semidiurnal Tides: $\frac{K_1+O_1}{M_2+S_2}>0.0<0.25$

Location of station	Value of harmonic constants H (ft)				Index: $\frac{K_1+O_1}{M_2+S_2}$	Spring range (ft)
	K_1	O_1	M_2	S_2		
Argentia, Newfoundland	0. 289	0. 324	2. 281	0. 675	0. 207	6. 3
Quebec, Quebec	0. 740	0. 690	5. 850	1. 380	0. 198	15. 5
Halifax, Nova Scotia	0. 340	0. 153	2. 046	0. 454	0. 197	5. 3
St. John, New Brunswick	0. 504	0. 374	9. 943	1. 629	0. 076	23. 7
Eastport, Me.	0. 476	0. 376	8. 468	1. 413	0. 086	20. 7
Portland, Me.	0. 459	0. 367	4. 356	0. 702	0. 163	10. 4
Boston, Mass.	0. 465	0. 380	4. 422	0. 717	0. 164	11. 0
Newport, R.I. (Narragansett Bay)	0. 212	0. 164	1. 690	0. 396	0. 180	4. 4
Bridgeport, Conn.	0. 295	0. 212	3. 185	0. 538	0. 136	7. 7
Willets Point, N.Y.	0. 319	0. 237	3. 619	0. 616	0. 131	8. 3
New York (The Battery), N.Y.	0. 328	0. 177	2. 138	0. 431	0. 197	5. 4
Sandy Hook, N.J.	0. 318	0. 164	2. 154	0. 447	0. 185	5. 6
Philadelphia, Pa.	0. 333	0. 244	2. 602	0. 298	0. 199	6. 2
Wilmington, N.C.	0. 250	0. 202	1. 978	0. 250	0. 203	4. 5
Charleston, S.C.	0. 335	0. 252	2. 445	0. 411	0. 206	6. 1
Savannah, Ga.	0. 364	0. 278	3. 497	0. 542	0. 159	8. 6
Mayport, Fla.	0. 269	0. 193	2. 143	0. 359	0. 185	5. 3
Miami Beach, Fla.	0. 136	0. 105	1. 203	0. 237	0. 167	3. 0
						Diurnal range
Anchorage, Cook Inlet, Alaska	2. 240	1. 251	11. 471	3. 250	0. 237	29. 0

TABLE 19.—*Types of Tides (With Index and Range) at Various Locations Along the Atlantic, Pacific, and Gulf Coasts of North America*—Continued

Mixed Tides Mainly Semidiurnal: $\frac{K_1+O_1}{M_2+S_2} \geq 0.25 \leq 1.5$

Location of station	Value of harmonic constants H (ft) K_1	O_1	M_2	S_2	Index: $\frac{K_1+O_1}{M_2+S_2}$	Spring range (ft)
St. John's, Newfoundland	0. 262	0. 213	1. 178	0. 486	0. 285	3. 5
Harrington Harbour, Quebec	0. 478	0. 474	1. 742	0. 576	0. 411	4. 9
Pictou, Nova Scotia	0. 667	0. 648	1. 373	0. 354	0. 761	3. 9
New London Conn.	0. 238	0. 166	1. 166	0. 228	0. 290	3. 1
Breakwater Harbor, Del.	0. 342	0. 282	1. 916	0. 344	0. 276	4. 9
Baltimore, Md.	0. 207	0. 204	0. 486	0. 082	0. 724	1. 3
Key West, Fla.	0. 290	0. 290	0. 565	0. 172	0. 787	1. 6
						Diurnal range
San Diego, Calif.	1. 096	0. 693	1. 788	0. 724	0. 712	5. 7
Los Angeles, Calif. (Outer Harbor)	1. 112	0. 704	1. 695	0. 665	0. 769	5. 4
San Francisco, Calif. (Golden Gate)	1. 195	0. 748	1. 796	0. 406	0. 882	5. 7
Astoria, Oreg. (Tongue Point)	1. 257	0. 739	3. 012	0. 676	0. 541	8. 2
Aberdeen, Wash.	1. 364	0. 800	3. 425	0. 873	0. 503	10. 1
Seattle, Wash.	2. 734	1. 503	3. 530	0. 839	0. 970	11. 3
Valdez, Prince William Sound, Alaska	1. 601	0. 986	4. 521	1. 533	0. 427	12. 0
Nome, Alaska	0. 317	0. 208	0. 366	0. 038	1. 300	1. 6

Mixed Tides Mainly Diurnal: $\frac{K_1+O_1}{M_2+S_2} > 1.5 < 3.0$

Location of station	Value of harmonic constants H (ft) K_1	O_1	M_2	S_2	Index: $\frac{K_1+O_1}{M_2+S_2}$	Spring range (ft)
South Boca Grande, Fla.	0. 410	0. 370	0. 371	0. 126	1. 569	1. 7
St. Petersburg, Fla.	0. 513	0. 477	0. 497	0. 159	1. 509	2. 3
Galveston, Texas (Galveston Channel)	0. 384	0. 364	0. 309	0. 098	1. 838	1. 4
Victoria, British Columbia	2. 056	1. 214	1. 223	0. 336	2. 097	6. 1
Dutch Harbor, Amaknak Island, Alaska	1. 088	0. 729	0. 852	0. 091	1. 927	3. 7

Diurnal Tides: $\frac{K_1+O_1}{M_2+S_2} \geq 3.3$ to ∞

Location of station	Value of harmonic constants H (ft) K_1	O_1	M_2	S_2	Index: $\frac{K_1+O_1}{M_2+S_2}$	Diurnal range (ft)
Pensacola, Fla.	0. 401	0. 384	0. 062	0. 021	9. 458	1. 3
Mobile, Ala. (Mobile River)	0. 466	0. 458	0. 054	0. 036	10. 267	1. 5
Biloxi, Miss. (Biloxi Bay)	0. 568	0. 514	0. 112	0. 091	5. 330	1. 8
St. Michael, Alaska	1. 378	0. 758	0. 586	0. 111	3. 065	3. 9
Sweeper Cove, Adak Island, Alaska	1. 342	0. 941	0. 623	0. 074	3. 275	3. 7

Chapter 7

The Classification, Designation, and Periodicity of Perigean Spring Tides, With Outstanding Examples of Accompanying Tidal Flooding From Recent History

It has been emphasized frequently in preceding chapters that the coincidence of perigee-syzygy with certain lunisolar positional relationships produces the highest known astronomical tides. The resulting proxigean and perigean spring tides—when associated with strong, persistent, onshore winds—have been responsible for a large number of instances of major tidal flooding experienced over long periods of history (see table 1). At the same time, among the examples of table 3, there is empirical evidence to show that the *ordinary spring tide*, when accompanied by sufficiently strong onshore winds, is also capable of causing coastal flooding conditions—although these are, for the most part, of far smaller magnitude.

It is imperative, therefore, that an evaluation be made of the particular characteristics which set each close perigee-syzygy alignment apart from other tide-augmenting circumstances as one especially susceptible to the production of major tidal flooding, when supported by the appropriate meteorological conditions. This analysis must also include other force-modifying factors involving the combination of the gravitational forces of the Moon and Sun—the most important of which are the respective phenomena of *priming* and *lagging*.

From an initial comparison of spring and perigean spring tides, involving the differences imposed by these latter two factors, a logical follow-on entails: (1) the establishment of a uniform system of classification for ordinary spring tides, pseudo-perigean spring tides, perigean spring tides, proxigean spring tides, and extreme proxigean spring tides, based upon the purely astronomical parameters which go into their production; (2) an investigation of various periodicities which govern the recurrence of exceptionally close perigee-syzygy alignments; (3) the representation of a considerable number of specific examples of tidal flooding associated with the foregoing different classifications of tides; (4) the provision of significant comparative data of astronomical, oceanographic, and meteorological nature relative to these cases of tidal flooding; (5) the development of a basic intensity scale for rating the probable magnitude of the tidal flooding event likely to accompany a given combination of astronomical and meteorological circumstances; (6) the derivation of a suitable numerical coefficient as a quantitative indicator to assist in evaluating the astronomical potential for tidal flooding subject to a given set of perigee-syzygy conditions; (7) a survey of the significance of rate of tide growth in producing especially intense coastal flooding situations, and of variable wind-coupling conditions in driving the astronomically raised perigean spring tides onshore; (8) the determination of a schedule of combined astronomical-meteorological conditions which make the coastline particularly vulnerable to tidal attack; (9) an analysis of the relationships between perigean spring tides and other oceanographic phenomena—such as the high water lunitidal interval, internal waves, turbidity currents, and the marked increase in the velocity of tidal currents; and (10) a consideration of possible correlations between the astronomical occurrence of perigee-syzygy and various other geophysical, selenophysical, and biological phenomena.

These factors will be discussed, in the above order, in this and the following chapter. A suitable system of classification for the various types of tides mentioned in (1) above must first be developed.

Comparison of Ordinary Spring Tides and Perigean Spring Tides

Reduced to the simplest terms, spring tides are caused by the reinforcing action of the gravitational force of the Sun with that of the Moon caused by the alignment of these two bodies in celestial longitude (or, alternatively, right ascension) at times of new moon (conjunction) or full moon (opposition). Accordingly, such tides occur without fail on the two occasions of syzygy in each synodic month. At these times, the daily range of the tides is increased by approximately 20 percent above the average. The effect of lunar variation (see p. 175) is to add 28″

to the lunar parallax at either new moon or full moon, regardless of the angular distance from perigee; however, some additional component is also added to the parallax by the lunar evection term, depending upon the Moon's anomalistic angle.

Certain other astronomically related factors may occur to cause considerable variations in the relative tide-raising forces associated with spring tides. These include: (1) the diurnal inequality, resulting from a large declination of the Moon; (2) a coincidence of either position of syzygy with (a) the summer or winter solstice, (b) the vernal or autumnal equinox, (c) other times at which the Moon and Sun reach the same declination, or (d) the time at which the Earth reaches its closest annual approach to the Sun (perihelion); and (3) a large zenith distance of the Moon. Since, however, these same factors may also act to modify perigean spring tides, none of these variable influences may be considered as distinguishing ordinary spring tides from the former type.

As in the case of all higher-than-usual tides, ordinary spring tides are subject to the action of sustained onshore winds in lifting the greater water levels produced onto the land. Although spring tides usually possess a much smaller flooding potential compared with tides of the perigean spring type, it must be recognized that they, too, have played a definite, although considerably less prominent and consistent role in major tidal flooding over the course of history. Despite the emphasis given in the present volume to perigean spring tides as a heavily documented contributing cause to coastal flooding as well as the special object of study, there is no intent to detract from the significance of the ordinary spring tide as an additional source of such flooding, given the necessary supporting conditions of very intense, sustained onshore winds.

However, in objectively evaluating the flooding potential of ordinary spring tides compared with that of perigean spring tides, certain definite astronomical factors exist which favor the latter for the production of severe coastal flooding when appropriate wind conditions prevail. These astronomical differences between ordinary spring tides and perigean spring tides will now be considered.

It has been repeatedly pointed out in previous chapters that one of the factors increasing the potential for tidal flooding in the case of perigean spring tides is a greater length of time during which the enhanced gravitational forces of Sun and Moon can act, associated with a longer tidal day. As has been shown, the principal lengthening of the tidal day is due to the increased velocity of the Moon at lunar perigee. By definition, a true ordinary spring tide is one separated in time as far as possible from perigee and thus lacking in the increased orbital velocity and necessary catch-up effects imposed thereby. From this cause alone, therefore, the ordinary spring tide is not accompanied by an increased tidal day. On the other hand, the astronomical alignment producing spring tides *is* influenced by the effect of lunar variation (see p. 165) which tends to increase the orbital velocity of the Moon at syzygy (and thereby lengthen the tidal day) and, as a function of lunar phase angle, the effects of priming and lagging which act respectively to shorten or lengthen the tidal day.

Concepts of Tidal Priming and Lagging

Although the mass of the Sun is 27,070,000 times that of the Moon, the average distance of the Sun from the Earth is 389 times that of the Moon. The comparative tide-raising forces of the Sun and Moon are directly proportional to the relative masses of the Sun and Moon and inversely proportional to the cube of their respective distances from the Earth. The effective tide-raising force of the Moon is, therefore, $^{11}\!/_{7}$ths that of the Sun, or the tide-raising force of the Sun is only $^{5}\!/_{11}$ths that of the Moon. In all tidal actions, the Earth's tidal waters accordingly more closely follow the position, angular motion, and relative distance of the Moon, but are modified by the corresponding solar factors.

Lunar Phase Effects—Qualitative Evaluation

In terms of the *elongation,* or changing angular distance between Sun and Moon in the sky consequent upon the lunar phases, this same tide-raising principle applies. The major axis of the Earth's hypothetical tidal force envelope is always directed toward a position which is the resultant of the gravitational force influences of both the Moon and the Sun. Except at times of conjunction (new moon) and opposition (full moon), when the directions of the Sun and Moon come into coincidence in longitude (or right ascension) the orientation of the resultant force vector in the direction of the combined gravitational attraction of the Moon and Sun always lies between these two bodies as seen from the Earth, but closer to the longitude of the Moon by a factor proportional to its greater tide-raising influence.

Priming and Lagging as Shown in Tide Curves

The repeating maxima and minima in the two composite sets of tide curves (figs. 44a–44b) showing the variations in the length of the true tidal day may readily be explained by an analysis of the changing phase relationships of the Moon with respect to the Sun.

As the result of the annual orbital motion of the Earth around the Sun, the Sun appears to move around the celestial sphere at the same speed as the Earth and in the same counterclockwise direction as viewed from the north pole of the ecliptic. As seen on the vault of the sky, this apparent movement of the Sun duplicates the 360° of the Earth's revolution in 365.25 days, at an average speed of slightly less than 1° per day. The apparent motion of the Sun is also in the same direction as the actual motion of the Moon in its orbit around the Earth. Whereas the Sun's apparent motion is approximately 1°/day, the Moon's orbital motion ranges from about 11.78° to 15.37°/day, and the Moon therefore achieves two successive alignments with the Sun from one syzygy position (new moon) to the next (full moon) in about 14–15 days.

At last-quarter phase, the Moon is 90° to the west of the Sun in celestial longitude but, in its eastward motion in orbit, the Moon reduces this angular separation at a rate of some 14°/day. Between last-quarter phase and new moon, the configuration of Earth, Moon, and Sun is such that the Sun lies ahead of the Moon (at a greater right ascension or longitude) and the Moon is overtaking the Sun. Because the Sun leads the Moon in the sky, the position of maximum amplitude of the Earth's tidal force envelope resulting from the combined gravitational attractions of the Sun and Moon is displaced to a position in advance of a line joining Earth and Moon by a considerable but rapidly lessening amount.

Each day, the Moon further closes the angular distance in elongation separating itself from the Sun, and the major axis of the tidal force envelope in turn swings continuously into closer alignment with the Moon (i.e., in a direction opposite to the orbital motion of the Moon and the rotational motion of the Earth).

The period required for any position on the rotating Earth to align itself twice with the major axis of the tidal force envelope represents the length of the *tidal day.* Since, with the major axis of the tidal force envelope moving in a direction opposite to the Earth's rotation, it takes any point on the Earth's surface somewhat less time to reach alignment with this force-axis, the tidal day is shortened proportionately.

1. Tidal Priming

It has been shown that, following last-quarter phase and with the Moon rapidly catching up on the Sun, the angle of separation (the elongation) between them is reduced. The gravitational influence of the Sun is added increasingly to that of the Moon and in a direction more nearly corresponding to that of the Moon as the two bodies come into closer alignment. From last-quarter phase to new moon, therefore, the tidal day is continually shortened and reaches a minimum at new moon. Exactly the same situation prevails between first-quarter phase and full moon, since the tidal force action is exerted along the line of syzygies. This phenomenon (called lunar "priming") accounts for the successive minima in the length of the tidal day shown in figs. 44a–44b.

2. Tidal Lagging

The greater relative speed of the Moon in its orbit compared with the apparent daily motion of the Sun likewise explains the opposite phenomenon which increases the length of tidal day following the syzygies and between new moon and first-quarter and full moon and last-quarter phases, respectively. Since the Moon is traveling faster than the Sun at each instant, the latter is effectively falling behind the position of the Moon. The major axis of the Earth's tidal force envelope which, as previously explained, follows the Moon's position far more closely, is in this case continually displaced away from the Sun. This displacement now is in the same direction as that of the Moon's revolution, and that in which the Earth is rotating on its axis. A catch-up time is required in the Earth's rotation. Thus, following the minima occurring at new moon and full moon, the tidal day is progressively lengthened between the new moon and first quarter and full moon and last quarter, respectively. This relationship is clearly indicated in the curves showing changing lengths of the tidal day in figs. 44a–44b. The shortening process thereafter resumes, as noted under section 1, above.

It is important to observe that the lengthening of the tidal day produced by the phenomenon of tidal lagging occurs prior to neap tides, when the tide-raising forces of Moon and Sun are directly opposed and minimized. The extension of the tidal day resulting from this cause does not, therefore, provide a meaningful contribution in augmenting the daily range of the tides as in the case of: (1) decreased lunar distance of the Moon from the Earth at perigee-syzygy; (2) an extreme proximity of the Moon to the Earth at lunar proxigee; or (3) the increased motion of the Moon in right ascension when it is at higher declinations.

F-68 (a)

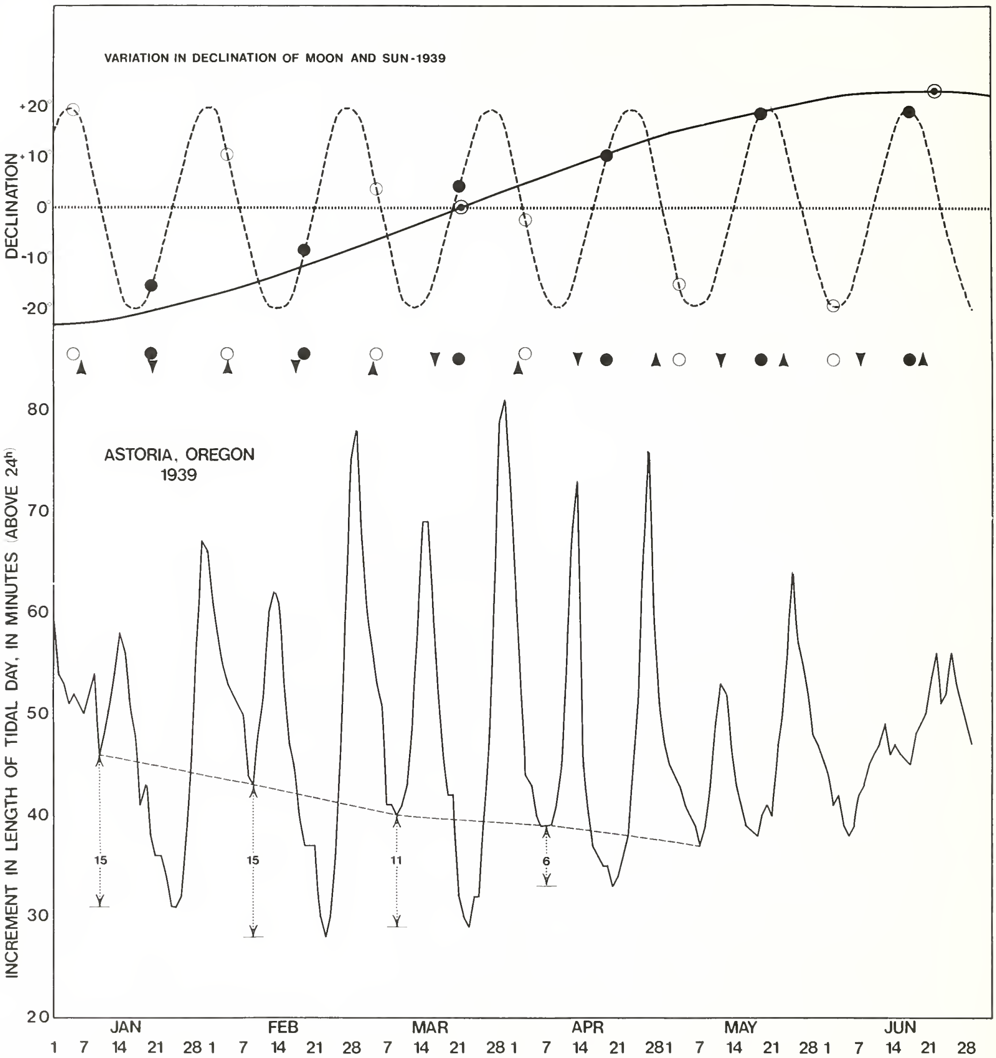


FIGURE 44a.—Variation in the length of the tidal day during 1939 January–June, shown as a function of the increment to be added to the time of the previous day's higher high water to establish the time of occurrence of HHW on the current day. The graph for an entire year is presented in figures 44a and 44b. A detailed analysis of these variations is contained in the main text.

F-68 (b)

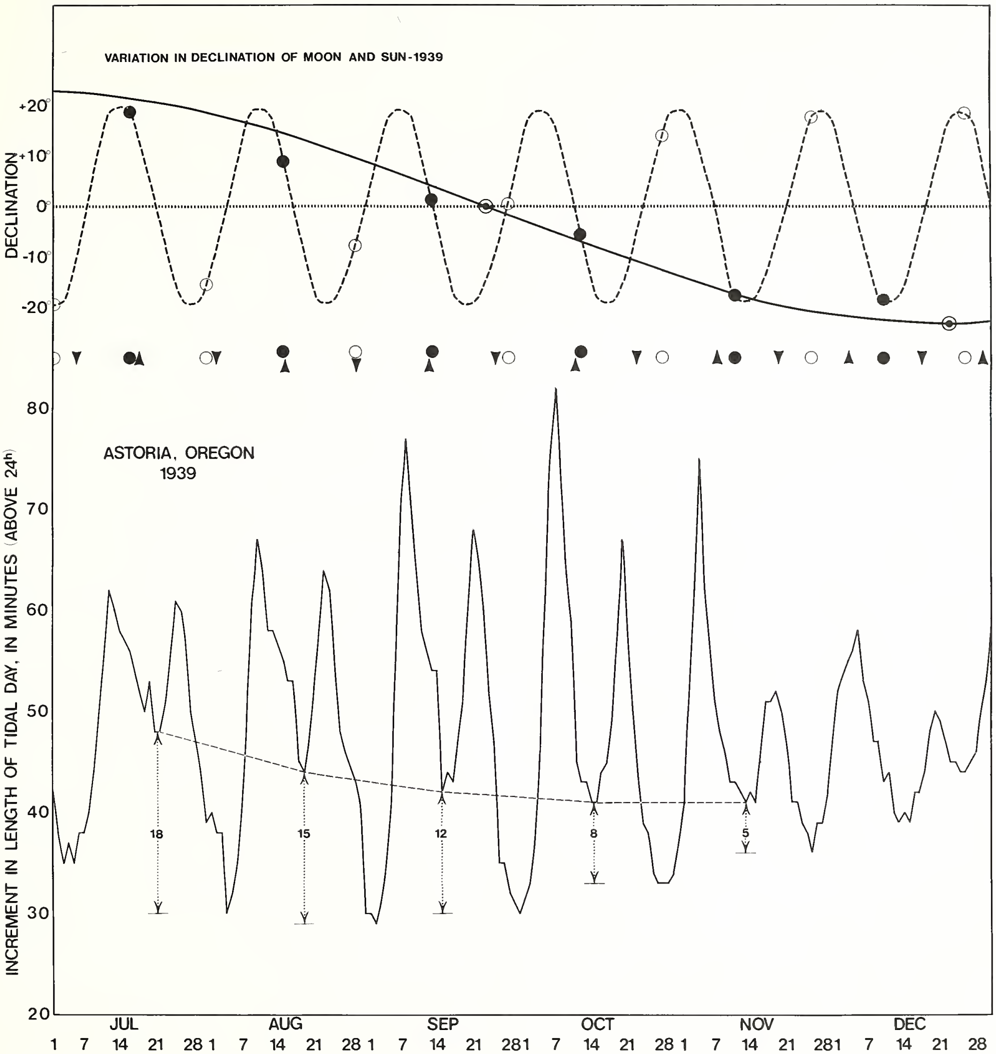


FIGURE 44b.—A graph containing data of the same nature as figure 44a, plotted for 1939 July–December. The technical interpretation of the changing maxima and minima of these curves is given in the text.

QUANTITATIVE ANALYSIS OF THE EFFECTS OF TIDAL PRIMING AND LAGGING

As in previous cases, the use of an actual example will serve to illustrate the various quantitative relationships involved between neap tides, ordinary spring tides, and perigean spring tides, as well as the modifications introduced by tidal priming and lagging. Restating the earlier qualitative description, the direct cause of these latter phenomena is the addition of two vector components indicative of the separate gravitational forces of the Sun and Moon, rather than that of the Moon alone. This vector sum representing the combined gravitational forces of the Sun and Moon and varying with the lunar phase is hereafter referred to as the *resultant force vector*. A meaningful evaluation of the effects of these two phenomena may be achieved by reference to figs. 45 and 46, and tables 20 and 21. In the two diagrams, vector arrows indicate, for each succeeding day, the directions and magnitudes of the combined gravitational forces of the Sun and Moon. The composite of these resultant force vectors (each symbolizing a mean daily magnitude and direction) serves to define the shape of the total tidal force envelope.

It should immediately be pointed out that this tidal force envelope representing the combined gravitational attractions of the Sun and Moon on the waters of the Earth during the course of the lunar month is not identical with the envelope of gravitational forces responsible for the instantaneous disposition of tidal high and low waters and their movements over the surface of the Earth during each tidal day. Both of these force envelopes are ellipsoids, and both are delineated by force components, but the larger force envelope shown in figs. 45 and 46 involves the changing pattern of lunisolar forces over an entire lunar month. The smaller ellipsoidal figure immediately adjacent to the Earth in these same figures (and also shown in fig. 2 of the appendix) represents the combination of all gravitational force components acting instantaneously on the tidal waters. This force envelope sweeps daily around the rotating Earth. With certain exceptions of nonastronomical nature subsequently to be discussed, the major axis of this second force envelope is aligned approximately with that of the Earth's envelope of tidal waters.

Although the tidal waters themselves do not actually "rotate" around the Earth due to the many inertial and geographic restraints imposed to their passage, the force envelope does so rotate once each tidal day. It is in this latter sense that it is safe to use the expression "diurnal rotation" in connection with the smaller ellipsoid (shown in elliptical profile) in figs. 45–46. With the passage of each succeeding day, the major axis of this smaller force envelope shifts continuously to follow the instantaneous orientation of the resultant force vector in the larger force envelope, representing one monthly lunation. Although certain other modifying factors prevent an exact coincidence between the instantaneous orientations of the resultant force vectors of these two ellipsoids, their orientations are obviously very closely related for any given position of the Moon and Sun in the monthly cycle of phases.

Relative Tide-Raising Forces at Quadratures and Syzygies

The instantaneous *magnitude* of the combined lunisolar force during each lunation is primarily a function of the phase angle of the Moon with respect to the Sun—varying from a minimum at quadratures (when the Moon's gravitational force on the Earth is imposed at right angles to that of the Sun) to a maximum at the syzygies (when the vector forces of the Sun and the Moon are applied along the same axis in space to reinforce each other). These conditions result in neap and spring tides, respectively. (See fig. 3, appendix.)

Column 7 of tables 20 and 21, in which the relative magnitudes of the resultant forces of the Sun and Moon have been computed for various times in a lunar cycle, shows this relationship clearly. For the purpose of convenience, the tide-raising force of the Moon is assumed to be unity, and that of the Sun to have its comparative value of $5/11$ or 0.455 that of the Moon. Thus, at quadratures (neap tides), the vectorial combination or resultant of the two forces approximates 1.03 to 1.19 and at the syzygies (spring tides) is the simple sum of the two, or 1.455. (See the note at the end of the following section.)

The numerical values of the forces specified above are only relative for any given angular orientation between Sun, Earth, and Moon. In terms of a quantitative evaluation, the particular value of these figures is to show the increase in lunitidal forces occurring between the situation producing neap tides and that producing spring tides. It must be borne in mind that the absolute magnitude of this resultant force will be modified by the many factors of changing distance, declination, etc., between Earth, Moon, and Sun as these bodies shift in relative position.

Confirmation of the Extended Duration of Peak Tide-Raising Forces at Perigee-Syzygy

However, column 7 also serves to reinforce one very important principle in regard to perigean spring tides—namely, the extended period of time within which the stronger combined forces of the Sun and Moon at perigee-syzygy are effective in producing higher-than-usual tides vulnerable to wind attack and potential tidal flooding.

Such a direct analysis of the basic lunisolar forces acting is possible through a comparison of the normal perigee-quadrature situation occurring on 1962 June 24 (table 21), with the close perigee-syzygy situation contributing to the great coastal flooding of 1962 March 6–7 (table 20). In the first example, with perigee occurring at quadrature, syzygy is necessarily more than 5 days away and, under the terms of reference previously established, the ensuing tides at new moon are defined as ordinary spring tides. In this case, the resultant maximum force of Moon and Sun defined by the peak value of 1.455 lasted only 1 day, and this maximum value stands out singularly from a lesser value on either side. During the coastal flooding of 1962 March 6–7, which (as noted later in this chapter) continued for five successive high tides, maximum or near-maximum forces of Sun and Moon (1.452 to 1.455) prevailed throughout a 2-day period and even longer. (*Note:* In order to standardize the trigonometric-vectorial reductions involved,

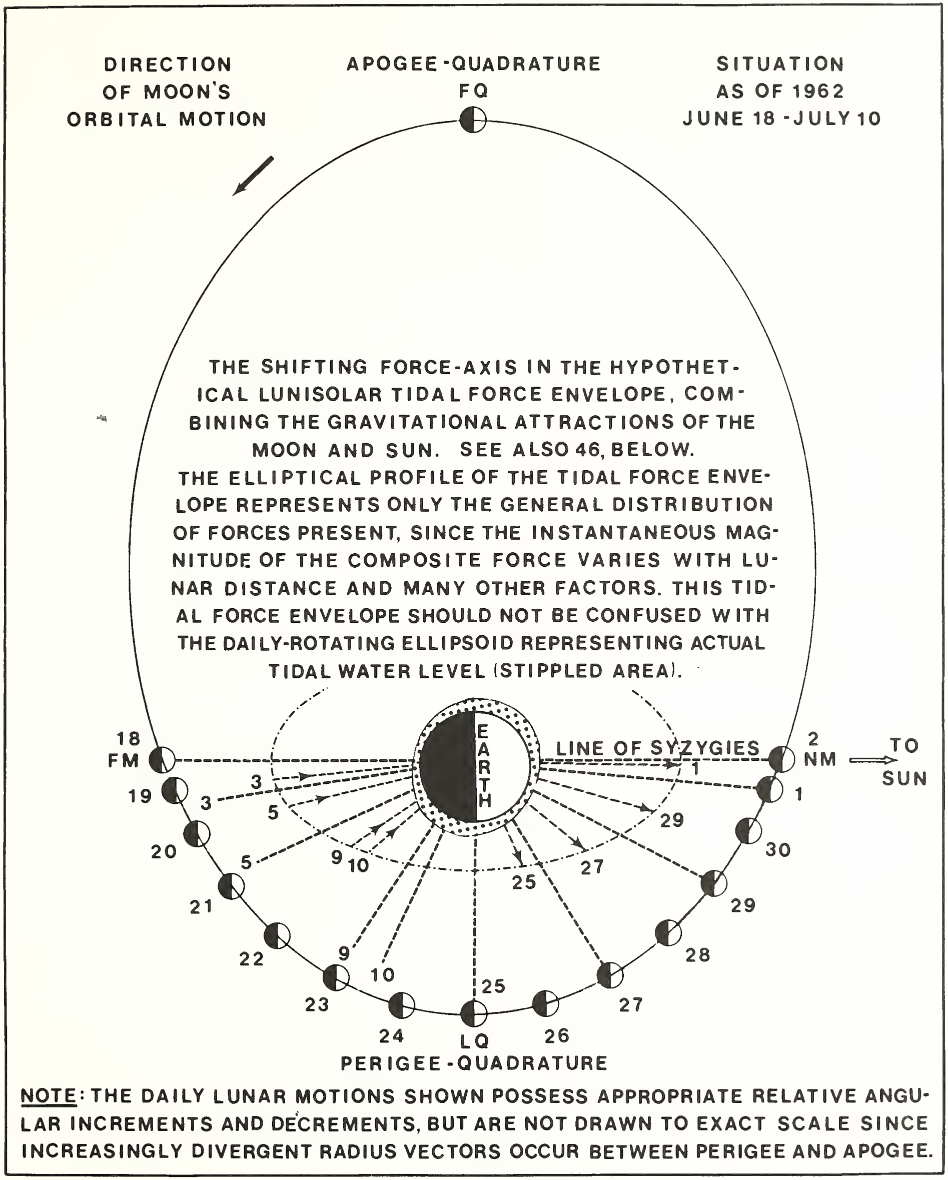


FIGURE 45.—Graphical representation of the basis for lunar priming and lunar lagging, as these phenomena affect the length of the tidal day. The situation depicted is that at perigee-quadrature. A detailed discussion and quantitative analysis of these effects form part of the main text.

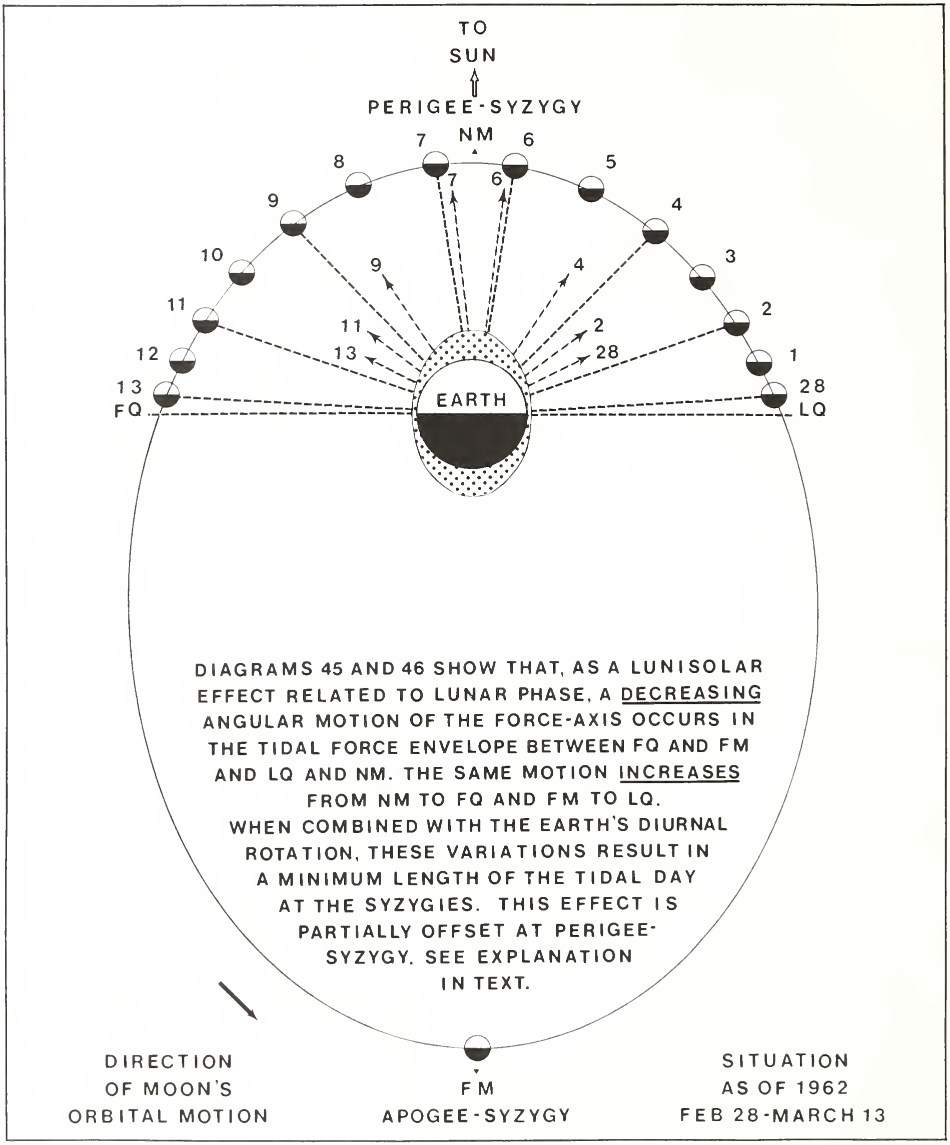


FIGURE 46.—Partial compensation of the effects of tidal priming and lagging at perigee-syzygy, in relationship to these same effects represented in figure 46 at perigee-quadrature. The corresponding amounts of acceleration or deceleration in the force-axis of the tidal force envelope in these two cases, both at and between the various phases of the Moon, may thus be intercompared.

TABLE 20.—*Effects of Tidal Priming and Lagging (at Perigee-Syzygy)*

(1) Date	(2) Lunar phase or configuration	(3) Moon's apparent longitude	(4) Daily change in longitude of Moon	(5) Sun's apparent longitude	(6) Moon's true elongation	(7) Magnitude of resultant tidal force	(8) Vector angle of resultant tidal force	(9) Daily change in resultant force vector	(10) Angle between Moon and resultant force vctor
1962		°	°	°	°	☾$_F$=1	°	°	°
Feb. 27. 0	LQ	240. 1170		337. 9209	−97. 8039	1. 041	−72. 1645		25. 6394
			12. 8803					−9. 9487	
28. 0		252. 9973		338. 9254	−85. 9281	1. 127	−62. 2158		23. 7123
			13. 2594					−9. 6888	
Mar. 1. 0		266. 2567		339. 9295	−73. 6728	1. 209	−52. 5270		21. 1458
			13. 6826					−9. 5754	
2. 0		279. 9393		340. 9333	−60. 9940	1. 284	−42. 9516		18. 0424
			14. 1251					−9. 5647	
3. 0		294. 0644		341. 9365	−47. 8721	1. 348	−33. 3869		14. 4852
			14. 5503					−9. 6185	
4. 0		308. 6147		342. 9394	−34. 3247	1. 399	−23. 7684		10. 5563
			14. 9119					−9. 6976	
5. 0		323. 5266		343. 9418	−20. 4152	1. 435	−14. 0708		6. 3444
			15. 1614					−9. 7690	
6. 0		338. 6880		344. 9436	−6. 2556	1. 453	−4. 3018		1. 9538
6. 5	P-S(NM)	346. 3157	15. 2585	345. 4444	0. 8713	1. 455	0. 5988	−9. 8049	0. 2725
7. 0		353. 9465		345. 9451	8. 0014	1. 452	5. 5031		2. 4983
			15. 1837					9. 7937	
8. 0		9. 1302		346. 9459	22. 1843	1. 431	15. 2968		6. 8875
			14. 9449					9. 7406	
9. 0		24. 0751		347. 9462	36. 1289	1. 393	25. 0374		11. 0915
			14. 5763					9. 6689	
10. 0		38. 6514		348. 9459	49. 7055	1. 340	34. 7063		14. 9992
			14. 1274					9. 6117	
11. 0		52. 7788		349. 9451	62. 8337	1. 273	44. 3180		18. 5157
			13. 6508					9. 6112	
12. 0		66. 4296		350. 9436	75. 4860	1. 198	53. 9292		21. 5568
			13. 1917					9. 7144	
13. 0	FQ	79. 6213		351. 9414	87. 6799	1. 115	63. 6436		24. 0363
			12. 7820					9. 9657	
14. 0		92. 4033		352. 9387	99. 4646	1. 028	73. 6093		25. 8553

Note: In columns 3 and 5, although the accuracy of the data on celestial longitudes of the Moon and Sun given in *The American Ephemeris and Nautical Almanac* for 1962 is sufficient to carry these figures to five decimal places, in degrees, they are rounded off to four places here and elsewhere in the volume in terms of adequacy for the immediate purpose. In the computations for column 7, the tide-raising force of the Moon is assumed to be unity, and the tide-raising force of the Sun 0.455 that of the Moon.

TABLE 21.—*Effects of Tidal Priming and Lagging (at Ordinary Syzygy)*

(1) Date	(2) Lunar phase or configuration	(3) Moon's apparent longitude	(4) Daily change in longitude of Moon	(5) Sun's apparent longitude	(6) Moon's true elongation	(7) Magnitude of resultant tidal force	(8) Vector angle of resultant tidal force	(9) Daily change in resultant force vector	(10) Angle between Moon and resultant force vector
1962		°	°	°	°	☾$_p$=1	°	°	°
June 24. 0		348. 9209		92. 0131	−103. 0922	1. 189	55. 0367		21. 8711
	P-Q(LQ)		14. 1996					10. 3923	
25. 0		3. 1205		92. 9669	−89. 8464	1. 100	65. 4290		−24. 4174
			14. 1780					−10. 6149	
26. 0		17. 2985		93. 9206	−76. 6221	1. 190	54. 8141		−21. 8080
			14. 1218					−10. 0337	
27. 0		31. 4203		94. 8744	−63. 4541	1. 270	44. 7804		−18. 6737
			14. 0258					−9. 5859	
28. 0		45. 4461		95. 8281	−50. 3820	1. 337	35. 1944		−15. 1876
			13. 8851					−9. 2248	
29. 0		59. 3312		96. 7819	−37. 4507	1. 389	25. 9696		−11. 4811
			13. 6974					−8. 9214	
30. 0		73. 0291		97. 7357	−24. 7066	1. 426	17. 0483		−7. 6583
			13. 4680					−8. 6587	
July 1. 0		86. 4971		98. 6894	−12. 1923	1. 447	8. 8396		−3. 8027
			13. 2051					−8. 3491	
2. 0	NM	99. 7022		99. 6432	0. 0590	1. 455	0. 0406		0. 0184
			12. 9243					8. 2369	
3. 0		112. 6265		100. 5969	12. 0296	1. 448	8. 2775		3. 7521
			12. 6438					8. 0851	
4. 0		125. 2703		101. 5506	23. 7197	1. 428	16. 3625		7. 3572
			12. 3825					7. 9850	
5. 0		137. 6528		102. 5043	35. 1485	1. 396	24. 3475		10. 8010
			12. 1586					7. 9497	
6. 0		149. 8114		103. 4579	46. 3535	1. 354	32. 2972		14. 0563
			11. 9875					7. 9953	
7. 0		161. 7989		104. 4115	57. 3874	1. 303	40. 2925		17. 0949
			11. 8814					8. 1403	
8. 0		173. 6803		105. 3650	68. 3153	1. 242	48. 4328		19. 8825
	A		11. 8491					8. 4107	
9. 0		185. 5294		106. 3185	79. 2109	1. 173	56. 8435		22. 3674
			11. 8955					8. 5859	
10. 0	FQ	197. 4249		107. 2719	90. 1530	1. 100	65. 4295		24. 7235

Note: In columns 3 and 5, although the accuracy of the data on celestial longitudes of the Moon and Sun given in *The American Ephemeris and Nautical Almanac* for 1962 is sufficient to carry these figures to five decimal places, in degrees, they are rounded off to four places here and elsewhere in the volume in terms of adequacy for the immediate purpose. In the computations for column 7, the tide-raising force of the Moon is assumed to be unity, and the tide-raising force of the Sun 0.455 that of the Moon.

the force magnitudes shown here do not contain any extra allowance above lunar force unity to accommodate this perigee-syzygy situation. Accordingly, in this purely vectorial analysis, the maximum tidal force value at perigee-syzygy calculated with this simplification does not exceed that at ordinary syzygy as is actually the case.)

Examples of Tidal Priming and Lagging

However, the principal function of these tables is to permit a quantitative verification of the manner in which the resultant lunisolar force vector either precedes or follows the position of the Moon in its orbit in the respective phenomena of priming and lagging. Although these relationships are shown graphically in figs. 45 and 46, it is impossible because of the continually changing proportions of an ellipse to represent the appropriate angular motions to a sufficiently accurate degree at the published scale. For descriptive purposes only, it is possible—by a smoothed consolidation of the data appearing in tables 20 and 21—to indicate the resultant force vectors in figs. 45 and 46 in at least approximately their correct positions either ahead of or behind the instantaneous position of the Moon, and with due regard to the phase and apsides relationships of the Moon at the time considered. The next step is to evaluate the effect of differences in angular orientation of the resultant force vectors upon the Earth's tides.

1. Application to Ordinary Spring Tides

With reference to the tide-influencing aspects of the Earth's diurnal rotation, the "catch-up" principle has been thoroughly described in previous pages. From an analysis of this principle, it has been determined that any influence which tends to accelerate the orbital motion of the Moon in the same direction as that in which the Earth is rotating will lengthen the tidal day. Since it is the mass and the gravitational force of the Moon rather than its geometrical figure that is involved in the production of the tides, this principle can be narrowed to permit, in substitution for the words "orbital motion of the Moon" above, the corresponding motion of the line of gravitational force action extending between the center-of-mass of the Moon and the Earth's surface. Conversely, any influence which tends to decelerate this line of force action joining the Moon and the Earth—thus increasing its effective displacement in a direction opposite to that of the Earth's rotation—causes a shortening of the tidal day.

A close examination of figs. 45 and 46 and the accompanying tables 20 and 21 reveals the nature of this particular influence upon the tides. In proceeding from either of the position of syzygy (NM or FM) toward the quadratures (FQ or LQ, respectively) it will be observed that the longitude angle (measured from the center of the Earth) between the direction of the Moon and the direction of the resultant lunisolar force vectors on successive days grows steadily larger. This follows logically from the circumstance that the Moon separates from the Sun through 90° of elongation between syzygy and quadrature. The significant fact, however, is that not only does the angle of separation (elongation) between Sun and Moon grow larger, but the angle separating the Moon from the direction of the resultant force vector also continuously increases. Between either position of quadrature and the ensuing syzygy, the reverse occurs and both the elongation and the angle between the Moon and the resultant lunisolar force vector diminish in value. (See cols. 6 and 10 in tables 20 and 21.)

This is one clue to the phenomena under consideration. The situation is exactly akin to that of the converging step increments by which a function approaches zero as a limit in the integral calculus. Between either position of quadrature and syzygy, each day's orbital motion of the Moon results in diminished angle between the Moon and the resultant force vector, approaching zero at syzygy. The incremental variations in those angles (second differences) themselves proceed toward increasing values between quadrature and syzygy, and toward decreasing values between syzygy and quadrature. Accordingly, the Moon is closing up faster on the resultant force vector the nearer it gets to syzygy. By taking differences between the successive values in col. 10 (tables 20, 21), it will be seen that this daily close-up rate is also noticeably greater at perigee-syzygy than at ordinary syzygy.

The rise and fall of the tides is very closely related to the times at which the Moon (and by extension, the lunisolar force vector) transits the local meridian of any place on the Earth's surface. The above-mentioned nonuniform displacements of the resultant force vector with respect to the position of the Moon therefore are of considerable significance in establishing not only the times of arrival of high and low water but also the total periods of time in which tide-raising forces of maximum intensity operate. As the resultant force vector moves ahead of the Moon's position through constantly *decreasing* angular values each day between quadrature and syzygy, the effect is a slowing down of the monthly rotation of the axis of the combined lunisolar force so that it, in effect, "drops back" in a direction opposite to that of the rotating Earth. A shorter period of time therefore elapses between two successive transits of this force axis across the local meridian of any place. This results, in turn in a continous shortening of the tidal day to a minimum value at the lunar syzygy.

As, between syzygy and quadrature, the resultant lunisolar force vector falls behind the position of the Moon, in a motion entailing steadily *increasing* angular values, the effect is continuously to accelerate this movement in a direction which is the same as that of the Earth's rotation. A longer catch-up time is thus required for any place on the rotating Earth to reach and pass this resultant axis of force. The period of time between two successive transits of the lunisolar resultant force vector is increased, and the consequence is an extension of the tidal day.

As pointed out above, although the orientation in space of the lunisolar resultant force vector and the major axis of the Earth's fluid envelope are not the same, the two normally accompany each other very closely. A circumstance thus arises in which, between quadrature and syzygy, the Earth's tidal bulge lies ahead of—and, subject to the Earth's rotation, reaches the meridian before—the Moon itself. This condition is known in tidal theory as *priming*. Between syzygy and quadrature, the tidal bulge transits the local meridian after the Moon, a phenomenon known as *lagging*.

The tidal day is generally defined as the interval of time between the occurrence of two successive higher high waters. The daily displacement of the lunisolar resultant force vector with respect to the Moon's position is in a forward direction near quadrature and retrograde near syzygy. Because the major axis of the Earth's tidal force envelope responds most closely to this motion, the tidal day acquires its greatest length near the quadratures, and its shortest length near the syzygies. As the result of this decreasing length of the tidal day between quadrature and syzygy and increasing length between syzygy and quadrature, the minimum length of the tidal day from this single cause is established at syzygy. This, then, is the situation as it exists at the time of ordinary spring tide, without any additional tide-raising influence being exerted by perigee.

2. Application to Perigean Spring Tides

It is important in terms of the classification of perigean spring tides given below to note that, in the case of ordinary spring tides, the greatest gravitational attraction produced by the combination of Sun and Moon (at syzygy) occurs at a time when the tidal day has its shortest length. Also, in figs. 44a, b it will be seen that the peaks of the curves (which represent the maximum lengths of the tidal day at quadratures) are much more uniform in height when at least 5 days separate syzygy and perigee—the classification criterion adopted in this work for an ordinary spring tide. In all cases, the peaks are separated by raised minima (resembling valleys between high mountains) which, however, are subject to a greater elevation in height when the length of the tidal day (e.g., at a time of perigee-syzygy) becomes greater.

A further enlightening feature concerning the nature of perigean spring tides is the direct contrast between the shallower depths of the curve troughs representing ordinary spring tides and the troughs of perigean spring tides immediately preceding or following an uplifted maximum associated with the latter type of tide. In the case of perigean spring tides accompanying a close alignment of perigee-syzygy, an apogee-syzygy situation must immediately precede or follow, within one-half a lunation, the corresponding condition of perigee-syzygy. In terms of the tide-raising force on the Earth, at apogee-syzygy, the gravitationally enhanced tidal effect resulting from the Moon's alignment with the Sun at syzygy is partially offset by the increased distance of the Moon from the Earth at apogee. At the time during which this reduced gravitational force acts, the Moon's orbital velocity is also reduced, due both to its greater distance from the Earth and to its approach to syzygy, shortening the tidal day. The considerably greater net shortening in the length of the tidal day consequent upon both of these causes provides an excellent basis for comparison with the shortening produced primarily by the syzygy effect in the case of an ordinary spring tide. The lengthening of the tidal day and uplifting of the curve minima at perigee-syzygy provides a still further contrast. It will be seen that the difference in amplitude (in units of time representing the length of the tidal day) between the lowest and highest minima of the curves in figs. 44a, 44b amounts to as much as 18 minutes. This difference represents the increase in the length of the tidal day accompanying a situation of close perigee-syzygy compared with a corresponding situation of apogee-syzygy in the same lunation.

The uplift effect in the curve minimum at the time of perigee-syzygy and increased depression of the minimum during the immediately preceding or following apogee-syzygy may be attributed to parallactic inequality. When either new moon or full moon coincide with perigee, the shortening of the tidal day described earlier for the ordinary syzygy condition is offset. At such times, the Moon's orbital motion is accelerated by its proximity to the Earth, and the Earth's rotational catch-up motion increases the length of the tidal day. Conversely, the recession of the Moon to its greatest monthly distance from the Earth at apogee reduces the Earth's gravitational attraction for the Moon and slows its orbital motion, decreasing the length of the tidal day and producing a deeper curve minimum.

A complete contrast exists in the case of the ordinary spring tide. When perigee coincides with quadrature, and either full moon or new moon is 90° removed from perigee, the average orbital speed of the Moon is only about 13° per day compared with a value which may reach more than 15° per day in the case of perigee-syzygy. The resulting considerably shorter length of the tidal day in the case of ordinary spring tides is further decreased by the effect of tidal priming previously described, and lacks any compensating increase as in the case of perigean spring tides.

A Proposed New System for the Quantitative Designation of Perigean Spring Tides

It is obvious from the step-by-step analysis of the very numerous astronomical factors which may influence the amplitude and range of perigean spring tides as outlined in previous chapters that various degrees and grades of these tides exist. Consequently, it becomes desirable for scientific purposes to establish a meaningful system for classifying these tides based upon the particular astronomical circumstances which both create them and determine the relative heights of the water they produce. In a succeeding section, the development of a suitable coefficient or index of tidal flooding potential also will be undertaken for these various classes of perigean spring tides, assuming them to be accompanied by the necessary meteorological conditions.

In this terminology-assigning process, certain new expressions, not presently in the language of either astronomy or tides, will be introduced which it is felt may be deserving of consideration in order to fill in an existing gap created by many years of comparative neglect of the subject area—and, in any event, to make the analysis of these tides more understandable.

Basis for the Classification of Perigean Spring Tides

The common denominator of all such tides, as frequently emphasized in the foregoing chapters, is the small time interval between perigee and syzygy, which leads—through solar perturbations of the lunar orbit—to the resulting close proximity of the Moon to the Earth, and a considerable increase in the tide-raising force. The reduced lunar distance from the Earth at times of perigee-syzygy is expediently (but in a mathematically inverse relationship) indicated by the geocentric horizontal parallax (π) of the Moon. It will become clear in connection with both astronomical and meteorological factors later to be discussed that the lunar parallax alone is insufficient substantively to evaluate the various categories of perigean spring tides in terms of their potential flooding ability if they become subject to continuous, strong, onshore winds. However, this quantity *is* suitable for a selective classification of such tides, based solely upon astronomical parameters.

In the subsequent analysis of tidal flooding potential, a practical numerical coefficient will be derived which represents the instantaneous value of the rate of change of the Moon's true anomaly at the time of perigee-syzygy as a function of the small separation-interval [a] between these components, the increased lunar parallax, and the greater speed of the Moon in orbit. The angle of the Moon's orbital motion with respect to the Equator is also considered. As has been seen, all these factors are of consequence in the differentiation between perigee-syzygy situations of varying tide-maximizing ability. And it must be emphasized again in terms of a later discussion of hydrographic and oceanographic influences that purely astronomical data are involved in the general classification scheme for perigean spring tides which follows immediately below. (See also figs. 47A, B, C, D, and table 22.)

[a] It is important to note that the difference between perigee and syzygy can be indicated either as an angular distance or in hours of time. Because of this dual quantification, the expressions separation-time and separation-interval have both been used in this work—the first primarily in part II, chapter 4 and earlier where the time difference was critical, the second in the present chapter and later. The term separation-interval, while at first glance seemingly redundant, is actually the more meaningful, since its two elements are representative of either arc or time.

1. Maximum Perigean Spring Tides (or Ultimate-Maximum Proxigean Spring Tides); Maximum Proxigean Spring Tides

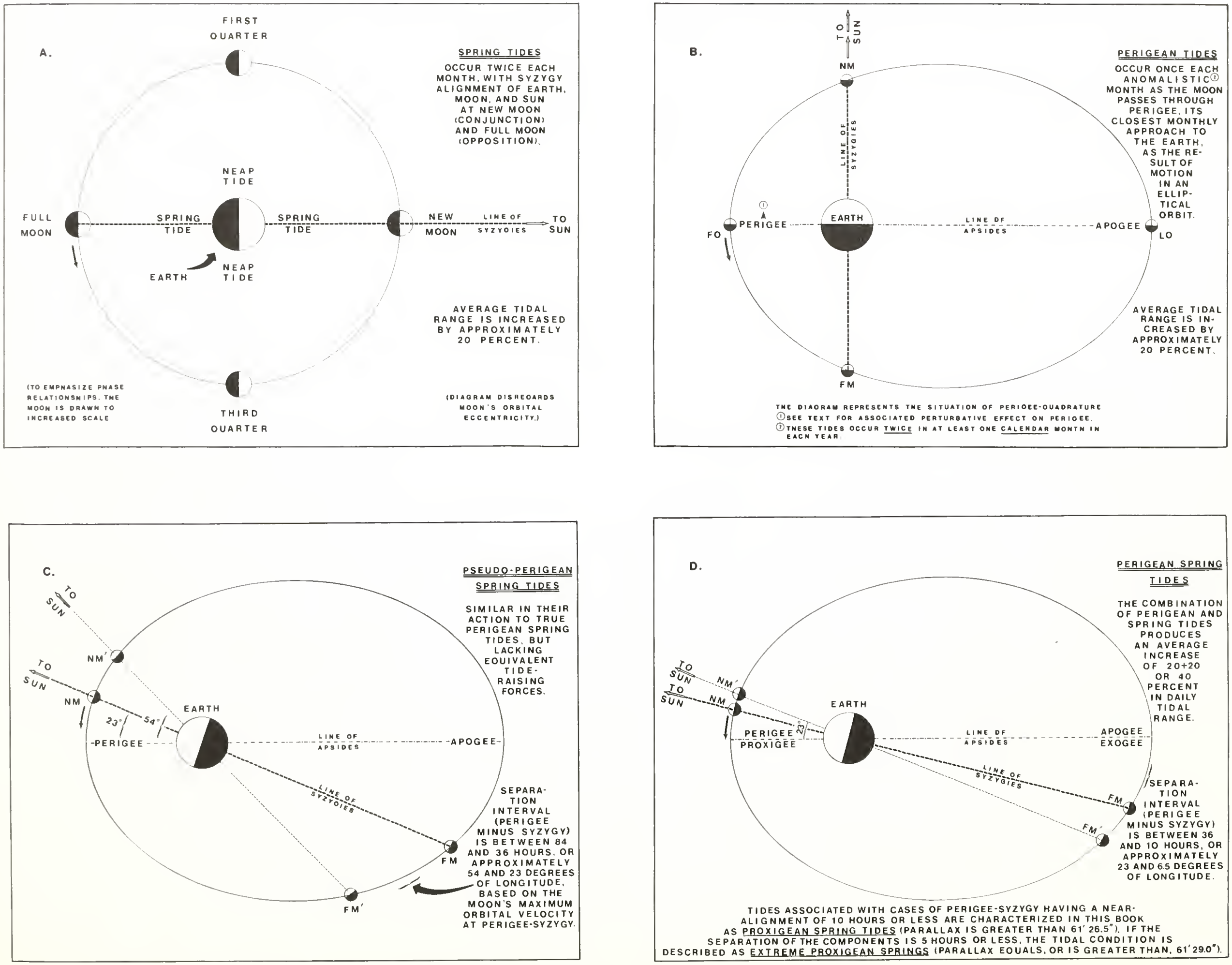
The theoretically largest possible value of the geocentric horizontal parallax which the Moon can attain is 61′32.0″ (see fig. 41). The conditions necessary to achieve this very high parallax presume that the full moon shall be simultaneously at proxigee-syzygy, with 1^h separation-interval, at one of the lunar nodes (i.e., coincident with the ecliptic, and with the Earth precisely at perihelion. (See pp. 203, 219.) Because this combination has not occurred any time in the past five centuries and will not occur again until A.D. 3300, it may be described as one of *maximum perigean spring tides* (or, for consistency in the present classification scheme, as an example of *ultimate-maximum proxigean spring tides*. The designation of *maximum proxigean spring tides* is appropriately given to those astronomical tides produced under a condition of proxigee-syzygy in which the resulting lunar parallax lies below its ultimate value, but within a range of 1.3″.

The use of the word "proxigean" in preference to the word "perigean" to distinguish such cases of unusual close proximity of the Moon to the Earth results from the

TABLE 22.—*Proposed Classification System for Perigean (Including Proxigean) Spring Tides*

Definition	Range* in lunar geocentric horizontal parallax at mean epoch of perigee-syzygy
1. Ultimate maximum proxigean spring tides	61′32.0″ ±0.1″
2. Maximum proxigean spring tides	≥61′30.7″<61′32.0″
3. Extreme proxigean spring tides	≥61′29.0″<61′30.7″
4. Proxigean spring tides	≥61′21.0″<61′29.0″
5. Perigean spring tides	≥60′20.0″<61′21.0″
6. Pseudo-perigean spring tides	≥59′00.0″<60′20.0″
7. Ordinary spring tides	≥55′00.0″<59′00.0″

*Because of the complexity of dynamic forces and conditions present, some exceptions to these arbitrarily established parallax ranges may exist on the part of tides otherwise responding to the average daily amplitude variations which occur within these individual categories.


A.
FIRST QUARTER
SPRING TIDES
OCCUR TWICE EACH MONTH, WITH SYZYGY ALIGNMENT OF EARTH, MOON, AND SUN AT NEW MOON (CONJUNCTION) AND FULL MOON (OPPOSITION).
NEAP TIDE
FULL MOON
SPRING TIDE
SPRING TIDE
NEW MOON
LINE OF SYZYGIES
TO SUN
EARTH
NEAP TIDE
AVERAGE TIDAL RANGE IS INCREASED BY APPROXIMATELY 20 PERCENT.
(TO EMPHASIZE PHASE RELATIONSHIPS, THE MOON IS DRAWN TO INCREASED SCALE
THIRD QUARTER
(DIAGRAM DISREGARDS MOON'S ORBITAL ECCENTRICITY.)
B.
TO SUN
NM
PERIGEAN TIDES
OCCUR ONCE EACH ANOMALISTIC② MONTH AS THE MOON PASSES THROUGH PERIGEE, ITS CLOSEST MONTHLY APPROACH TO THE EARTH, AS THE RESULT OF MOTION IN AN ELLIPTICAL ORBIT.
LINE OF SYZYGIES
①
PERIGEE
EARTH
LINE OF APSIDES
APOGEE
FO
LO
AVERAGE TIDAL RANGE IS INCREASED BY APPROXIMATELY 20 PERCENT.
FM
THE DIAGRAM REPRESENTS THE SITUATION OF PERIGEE-QUADRATURE
① SEE TEXT FOR ASSOCIATED PERTURBATIVE EFFECT ON PERIGEE.
② THESE TIDES OCCUR TWICE IN AT LEAST ONE CALENDAR MONTH IN EACH YEAR
C.
TO SUN
PSEUDO-PERIGEAN SPRING TIDES
SIMILAR IN THEIR ACTION TO TRUE PERIGEAN SPRING TIDES, BUT LACKING EQUIVALENT TIDE-RAISING FORCES.
NM'
TO SUN
NM
EARTH
23°
54°
-PERIGEE
LINE OF APSIDES
-APOGEE-
LINE OF SYZYGIES
SEPARATION INTERVAL (PERIGEE MINUS SYZYGY) IS BETWEEN 84 AND 36 HOURS, OR APPROXIMATELY 54 AND 23 DEGREES OF LONGITUDE, BASED ON THE MOON'S MAXIMUM ORBITAL VELOCITY AT PERIGEE-SYZYGY.
FM
FM'
D.
PERIGEAN SPRING TIDES
THE COMBINATION OF PERIGEAN AND SPRING TIDES PRODUCES AN AVERAGE INCREASE OF 20+20 OR 40 PERCENT IN DAILY TIDAL RANGE.
TO SUN
NM'
TO SUN
NM
EARTH
PERIGEE
PROXIGEE
23°
LINE OF APSIDES
APOGEE
EXOGEE
LINE OF SYZYGIES
SEPARATION INTERVAL (PERIGEE MINUS SYZYGY) IS BETWEEN 36 AND 10 HOURS, OR APPROXIMATELY 23 AND 6.5 DEGREES OF LONGITUDE.
FM
FM'
TIDES ASSOCIATED WITH CASES OF PERIGEE-SYZYGY HAVING A NEAR-ALIGNMENT OF 10 HOURS OR LESS ARE CHARACTERIZED IN THIS BOOK AS PROXIGEAN SPRING TIDES (PARALLAX IS GREATER THAN 61′ 26.5″). IF THE SEPARATION OF THE COMPONENTS IS 5 HOURS OR LESS, THE TIDAL CONDITION IS DESCRIBED AS EXTREME PROXIGEAN SPRINGS (PARALLAX EQUALS, OR IS GREATER THAN, 61′ 29.0″).

degree of selectiveness of the Latin and Greek prefixes involved in these respective terms. In a secondary usage to its more familiar concept of "around" (i.e., "circumscribing"), the Greek prefix *peri* also has a connotation of "near." The suffix *gee* (from the Greek *gē*) designates the Earth, so that the expression *perigee* properly implies nearness of the Moon to the Earth. In this sense, the word defines the point of the Moon's closest monthly approach to the Earth in its elliptical orbit around it.

However, this single term permits no indication of the relative closeness of the perigee position itself which, as has been seen, may vary within significantly wide limits subject to solar perturbations. For more accurate nomenclatural purposes, the suggested words "proxigee" and "proxigean," with prefix *proxi* from the Latin superlative form *proximus* meaning "nearest," connote both a position and an instant of unusual proximity of the Moon to the Earth. Without altering the time-honored concept of the word "perigee," the additional term "proxigee" allows for the more selective designation of a situation involving a *particularly close perigee.* Supplementary descriptive modifiers then complete the classification scheme.

One factor of immediate note in this connection is that the use of the prefix *proxi* together with the suffix *ge(e)* brings a Latin and a Greek root immediately into apposition, a procedure which might be frowned upon by those concerned with the origins and orthography of scientific terminology. An alternate choice for *proxi* might be the use of the prefix *epi,* which is itself a Greek root. However, because this prefix possesses such a wide range of possible meanings—including "on" (or "upon"), "at," "besides," "after," "over," "outer," and "anterior," all in addition to "near to"—it is not nearly as suitable, in a semantic sense, as is the prefix *proxi.* The prefix *epi* lacks in every way the fine points of distinction which go with the prefix *proxi,* whose exact meaning is so familiar both to scientific and general audiences in the words "proximal," "proximate," and "proximity."

A thorough review of unabridged dictionaries and of words forming, for the most part, a complement of the international scientific vocabulary (ISV) reveals the very large number of early, middle, late, and new Latin words which have come down to the modern period from original Greek sources. Thus, in a very great number of cases, it would appear to be senseless to distinguish between their primary Latin or Greek origins, since the words have appeared, at the same or different times, in both languages with but slight modifications in spelling. Such words are definitely not peculiar to either language and their interlingual mixture should provide no major concern.

To drive this point home, a brief summary (table 23) is appended herewith containing representative examples from among a large number of similar cases present among English scientific and technical vocabularies. This abbreviated table shows clearly that—especially among the words of modern-day origin but formed variously from Greek, Latin, English, French, Spanish, and Arab roots—prefixes and suffixes are joined almost indiscriminately. This is particularly true of more recent additions to the scientific vocabulary where the restraints imposed by the origin of a word by any one country are no longer necessary.

TABLE 23.—*Examples of scientific and technical terminology in the English language involving interlingual combinations of prefixes and suffixes*

Greek-Latin	*Latin-Greek*
peri/martium	semi/logarithmic
peri/jove	co/logarithm
peri/saturnium	super/adiabatic
pseudo/conglomerate	super/panchromatic
pseudo/fluorescence	non/mathematical
thermo/pile	extra/atmospheric
thermo/couple	bi/chloride
thermo/electric	bi/chromate
di/sulphide	bin/oxide
dyna/motor	bin/iodide
hyper/space	electro/lyte
auto/mobile	electro/kinetics
meso/tron (meson)	electro/phorus
photo/electric	spectro/bolometer
hemi/demi/semi/quaver	spectro/heliograph
Latin-Middle (or Old) English	*Latin-French (or Middle or Old French)*
sub/giant	electro/jet
infra/red	gravi/meter
flux/gate	multi/stage
multi/foil	*French-Greek-Middle Latin*
Satur/day	kilo/par/sec
counter/glow	*Greek-French*
ultra/high (frequency)	thermo/nuclear
Latin-Arabic	photo/gravure
alt/azimuth (instrument)	photo/montage
co-/azimuth	micro/fiche
Latin-Spanish (or Old Spanish)	
circum/zenithal (arc)	
super/cargo	

FIGURE 47, A,B,C,D.—A comparison of four different astronomical configurations and alignments which result—both through the combined lunisolar gravitational force action and an increasingly more exact orientation between the lines of syzygies and apsides—in proportionately higher tides. In conjunction with table 22, a suggested classification scheme for various amplitudes of perigean spring tides is also represented by this composite chart.

Without in any way advocating the introduction of such a surficial inconsistency other than by the statement that the use of the prefix *proxi* in every logical way "belongs," it may readily be seen from the table that ample precedent exists for such apparently discrepant prefix-suffix combinations where the combination involved is more meaningful.

It is important in consideration of the specialized and valuable roles of both chemical handbooks and unabridged dictionaries to include one further comment. Actually, if a true adherence to a consistent policy is used, such chemical radicals as chloride, chromate, oxide, or iodide, which originate from Greek words designating the chemical elements chlorine, chromium, oxygen, and iodine, respectively, should possess the corresponding Greek prefix *di* rather than the Latin prefixes *bi* or *bin(i)* which they now have. Similarly, the word sulphide, originating from the Latin word for sulphur should, for the sake of consistency, possess the Latin prefix *bi* instead of the Greek *di.*

In the proposed new classification, the position of extraordinary recession of the Moon from the Earth along the line of apsides 180° from proxigee (either preceding or following) would be termed *exogee* (from the Greek prefix *exo,* meaning "far from" and suffix *gē,* "Earth") as the counterpart of apogee.

It is emphasized that the preceding two classes of tide require the reinforcement of an extremely close proxigee-syzygy alignment by the other astronomical factors noted in the first paragraph of this section in order to achieve the maximum lunar parallax range cited, in excess of 61′30.7″ (the upper limit of the next tidal category). This circumstance has occurred (at instants of proxigee) only 14 times in the past 376 years. Appropriately, therefore, the use of the word "maximum" serves to distinguish between these tides produced by the combination of extremely favorable circumstances and those belonging to the succeeding category of tides.

By contrast, the tides of this next group are in no way related to the position of the Moon at a lunar node. They are, in fact, produced by an entirely different set of astronomical circumstances which results in an extraordinarily large value of the lunar parallax. As will be seen, these above-normal tides may be generated even with the Moon at rather high celestial latitudes, so long as it is in the same declination plane with the Sun.

2. Extreme Proxigean Spring Tides

Of considerably more consistent, but still infrequent occurrence (see table 13) among the 400-year tabular printout represented by table 16—and in no way following a regular chronological pattern—are those perigean spring tides which, for lack of any existing classification system are, in this volume, designated as *extreme proxigean spring tides.* In manner of dynamic origin, they possess certain of the same force-amplifying elements as those described in the preceding section. However, neither the lunar parallax produced, nor the accompanying astronomical tides, achieve the absolute maximum values associated with this first category.

Through an analysis of all cases recorded in the 400-year printout, the lunar parallaxes characteristic of this group range between ≥ 61′29.0″ and <61′30.7″. The greatest separation-interval between proxigee and syzygy encountered among the 39 examples bounded by these parallax limits in table 13 is $\pm 5^h$. Of considerable importance to the creation of the large parallax values, therefore, is the very consistent, close alignment of proxigee and syzygy in all cases.

But a second, strongly contributing factor in this category of tides is the circumstances that the tide-raising forces of the Sun and Moon are also exerted in the same declinational plane in each example, thus reinforcing the gravitational effect of alignment in longitude between the two bodies at proxigee-syzygy. The result of these concurrent lunisolar alignments in two coordinates is to increase the eccentricity of the lunar orbit and thus also the lunar parallax. The proxigee distance of the Moon from the Earth is diminished in proportion. As indicated on page 199, the further location of the Moon at full moon and near solar perigee also play a significant role in this force-enhancing situation. Although the coplanar alignment of the Moon and Sun may ordinarily occur on either the same or opposite sides of the Earth, in the latter case the two bodies are 180° from each other, resulting in the force differences previously noted (see p. 214). Although the maximum negative solar declination (solstitial) is −23½°, as seen in table 13 such approximately coplanar gravitational reinforcements can take place at slightly higher positive declinations of the Moon, especially when the nearly coplanar relationship occurs close to the time of perihelion.

3. Proxigean Spring Tides

At about 18-month but irregular intervals of time, a more exactly commensurable relationship between the synodic and anomalistic months creates a separation-interval between perigee and syzygy which is considerably less than average. This in turn results in an especially close distance (here termed proxigee) of the Moon from the Earth and a substantially increased lunar parallax. The arbitrarily established values of the parallax for this category lie between ≤61′26.5″ and <61′29.0″. The limiting value of the separation-interval is $\leq 10^h$.

As will be seen by comparison with the immediately succeeding category, a condition of proxigee-syzygy therefore represents, by definition, a particularly close approach of the Moon to the Earth and, by implication, in order to cause this, an unusually close alignment of perigee-syzygy. The tides of exceptional amplitude which result from this reduced distance of the Moon from the Earth and the correspondingly increased gravitational attraction of the Moon on the Earth's tidal waters—coupled with the pull of the Sun at syzygy—are referred to throughout this work as *proxigean spring tides*. In the computer printout (table 16) covering the 400-year period 1600–1999, a qualifying value of the parallax (at the time of proxigee) and corresponding proxigee-syzygy situation occurs, based on an actual average, once in each 1.46 calendar years.

4. Perigean Spring (or Perigee-Spring) Tides

These are the technical expressions which traditionally have been used to designate tides (possessing approximately 40 percent greater mean range) that result from any condition of near-alignment of perigee and syzygy. Either of these alternate terms as heretofore used collectively encompasses all of the other categories discussed in this list.

For the purpose of the present classification, the term is confined to tides produced by an astronomical condition involving a relatively close, but not unusual alignment of perigee-syzygy. If the separation-interval between perigee and syzygy is chosen as ±24 hours, such tides occur, on the average, three or four times in each tropical (ordinary) year. Two of the associated perigee-syzygy alignments are invariably closer than the other two, and the tides raised are slightly higher in these cases.

Perigean spring tides could, therefore, be regarded as the generic model, of which the other examples included in the present classification system are special adaptations.

This category—because of the far greater frequency in the number of cases represented which offer the possibility of simultaneous combination with strong, persistent, onshore winds—is responsible for by far the greatest number of cases of tidal flooding, but by no means the most severe cases, unless accompanied by a hurricane. As a matter of comparison, the separation-intervals and lunar parallaxes are given in tables 1 and 16, while news accounts of the relative severity of tidal flooding are provided for many cases in table 5. The predominance of major tidal floods at proxigee-springs and the greater frequency in the number of cases of tidal flooding at perigean spring tides are thus easily verified.

The mechanism of production of this general category of perigean spring tide has been explained both in the Technical Commentary accompanying part I, chapter 1, and elsewhere throughout the work and need not be repeated here. The arbitrary limits of parallax for this category, established from a detailed analysis of table 16 as well as the tidal flooding events encountered in the present study, are from $\geq 60'20.0''$ to $< 61'26.5''$. The perigee-syzygy separation-interval which seems optimally to represent the average situation in this category susceptible to tidal flooding (emphasizing again *not* the most severe cases) ranges from $\leqq \pm 10^h$ to $\leqq \pm 36^h$.

The computer printout of table 16, with an upper limit of $\pm 24^h$, does not include all of the perigee-syzygy alignments within $\pm 36^h$ responsible for *perigean spring tides* according to the present classification system. From an evaluation of the historic record, this particular category of tides—when accompanied by the appropriate winds—appears realistically to account for the great majority of cases of coastal flooding (exclusive of those caused by hurricanes). The addition of a 12-hour extension to the present printout data over a period of 400 years would, however, make the list prohibitively long for publication.

5. Pseudo-Perigean Spring Tides

This designation has been given in the present work to a group of tides whose perigee-syzygy interval lies just beyond the upper limit for perigean spring tides. However, they are produced close enough to even a comparatively wide alignment of perigee-syzygy to acquire some of the general characteristics of perigean spring tides in terms of increased amplitude and rapidity of tide growth. Some of the other tide-amplifying factors mentioned in previous chapters (such as coplanar alignment of Moon and Sun, etc.) may provide additional support to the weaker perigee-syzygy effects present.

Given sufficiently strong and lasting accompanying onshore winds, some surprisingly high tides and associated coastal flooding events have occurred among the examples of this type of tides listed in tables 1 and 5.

The parallax limits for this category have been set, for the purpose of consistency throughout this work, as between $\geq 59'00.0''$ and $< 60'20.0''$. The corresponding separation-interval which seems best to define these cases is from $\leqq \pm 36^h$ to $\leqq \pm 84^h$. Some few exceptions of an hour or so in excess of the upper limit have been permitted where the particular characteristics of the tide appear to dictate the logic of these minor extensions beyond the arbitrarily chosen limit.

6. Ordinary Spring Tides

Finally, the category of *ordinary spring tides* is used to define that situation in which perigee is separated from syzygy by more than $\pm 84^{h}$ and up to $\pm 120^{h}$. At a position more than 5 days away from perigee, an existing syzygy condition will generally converge toward, and be gravitationally weakened by, the increasing lunar distance at the immediately following or preceding position of apogee. An apogee-syzygy alignment ultimately results.

The *true* spring tide, to be completely unaffected by the influence of either perigee or apogee (including factors consequent upon both the lunar distance and velocity in orbit) must be separated by the entire 5 days from perigee and approximately 8–9 days from apogee. (The interval between perigee and apogee is one-half of an anomalistic month, or 13.7774 days, but the Moon moves faster over the portion of its orbit closest to perigee and the distances from perigee and apogee are thus unequally divided in terms of time.)

The parallax limits for this category of tides correspond roughly to a range from $\geq 55'00.0''$ to $< 59'00.0''$.

Periodic Relationships

The various astronomical relationships governing repetition of the phenomenon of perigee-syzygy will now be discussed.

The Mean Period Between Successive Occurrences of Perigee-Syzygy

According to the origin selected from which to measure the motion of the Moon, this body may have several different periods of revolution around the Earth. Detailed explanations of the synodic and anomalistic months have been included on pages 126, 130 and will not be repeated. The length of the *synodic month* is 29.530588 mean solar days. It is the period of time required for the *mean moon* to orbit from conjunction to conjunction, assuming it has a constant, average daily motion relative to the position of conjunction. However, this position is itself subject to small variations caused by perturbations in the lunar orbit, and the above period is an average for many circumstances, including the effects of parallactic inequality.

The length of the anomalistic month is 27.554550 mean solar days. It represents the period of time it takes the Moon to revolve in its orbit from one perigee to the next. The anomalistic month is shorter than the synodic month because of the extra time required in the latter case for the Moon to catch up with the Earth's orbital motion in the same direction and to achieve an alignment in celestial longitude between the Earth, Moon, and Sun at times of new or full moon.

The actual difference between the synodic month and the anomalistic month is

$$29.530588 - 27.554550 = 1.976038 \text{ mean solar days}$$

In consequence, once each synodic month, or lunation, the synodic month gains approximately 2 days on the anomalistic month. This means that, following a situation in which the Moon, Earth, and Sun are closely aligned at perigee-syzygy (assumed, for this present case, to occur at new moon) the difference between the lengths of the anomalistic and synodic month will cause the positions of perigee and new moon to diverge gradually from each other.

In each synodic month, the mean moon revolves through 360° of arc with respect to the position of conjunction, at an average rate of

$$360°/29.530588 = 12.19074947°/\text{day}$$

However, this mean daily motion of the Moon does not reveal the wide variations in the Moon's angular velocity previously discussed, and caused by parallactic inequality, solar perturbations, and other factors.

During each anomalistic month, the mean moon also revolves through 360° with respect to the position of perigee, at an average rate of

$$360°/27.554550 = 13.06499290°/\text{day}$$

Since this value has been observationally established, it includes the effect of an assumed mean revolutionary motion of the lunar line of apsides (and hence perigee itself) in the same direction as the revolutionary motion of both the Moon and Earth (see p. 177).

The daily angular gain of the anomalistic revolution over the synodic revolution is

$$13.06499290° - 12.19074947° = 0.87424343°/\text{day}$$

Since the synodic period is 29.530588 days, at a time approximately 0.5 month or 14.765294 days after new moon, full moon will occur. In this same 2-week period, the gain of the Moon's position over the line of apsides will be the equivalent of

$$0.87424343°/\text{day} \times 14.765294 \text{ days} = 12.908461°$$

which is less than one day's motion for the Moon. Subject to the previously stipulated conditions, the Moon, in its orbital revolution, cannot attain a position much more (and quite possibly less) than this amount ahead of the position of apogee. When the new moon occurs within less than a day of perigee, the succeeding full moon will normally fall within less than a day of the next following apogee. The perturbational motion of the line of apsides itself may be disregarded as of minor consequence during this lunar half-revolution since, over this interval between perigee and apogee, the motion is partially forward and partially retrograde.

For this daily gain to add up to the equivalent of one revolution of 360° requires

$$360°/0.87424343°/\text{day} = 411.7846216 \text{ days}$$

The full 411.78-day cycle is known as "the evectional period in the Moon's parallax," and since an early time has appeared variously throughout computational procedures for the tides, in connection with the synodic periods of the semidiurnal and diurnal tidal constituents. (See, for example, page 163 in *Manual of Harmonic Analysis and Prediction of Tides,* USC&GS (NOS) Special Publication No. 98 (1941); also table 2 of "Auxiliary Tables for the Reduction and Prediction of Tides," page 194 in the annual *Report of the Superintendent of the U.S. Coast and Geodetic Survey for 1894,* Part II). This interval of 411.78 days represents the *average* period of time required for a perigee-syzygy alignment of Sun, Earth, and either new moon or full moon, once having been attained, to occur next again at the *same phase.*

But since a near-concidence between perigee and syzygy which takes place at new moon results in a second close alignment between the line of syzygies and the line of apsides before the Moon returns to its new phase, successive occurrences of perigee-syzygy and apogee-syzygy alternate. Alignment of perigee and syzygy at new moon is followed by alignment of apogee and syzygy at full moon. At one perigee-syzygy alignment in each sequence, the two components converge toward a least separation. After this smallest separation-interval is attained, the interval increases with each lunation for some 3 months, then again decreases. Thus, the minimum time for a recurring near-coincidence between perigee and either conjunction *or* opposition is, *on the average*

$$411.7846216/2 = 205.892318 \text{ mean solar days}$$

(cf., table 39, "Synodic Periods of Constituents," in *Manual of Harmonic Analysis and Prediction of Tides.*)

This average period of time assumes that the mean values for the synodic and anomalistic months previously specified possess a constant and invariant value. The lengths of these individual lunar months actually vary considerably. As has been noted in chapter 6, those synodic and anomalistic months which contain the phenomenon of perigee-syzygy are the longest, but with the anomalistic months increasing considerably more than the synodic months under such circumstances (see table 17). During those anomalistic months whose lengths are increased to more than 28.5 days by virtue of a close perigee-syzygy alignment, the mean motion of the Moon is reduced to 360°/28.5° or 12.6° per day with respect to the mean position of perigee. (In the remaining anomalistic months of the lunar year, whose lengths are usually >1 to <5 days shorter than the synodic month, the mean motion of the Moon with respect to perigee varies from about 12.7° to 14.5° per day, on the average.) The previously noted daily angular gain of the anomalistic month over the synodic month is thus decreased from 0.87°/day to 0.5°/day at times of close perigee-syzygy alignments.

Because the daily angular gain of the anomalistic motion over the synodic motion is less, the lengths of the corresponding months come more nearly into agreement. In addition, the length of time required for this daily gain to add up to the equivalent of one full revolution of 360° is greater, and the actual minimum period between the closest occurrences of perigee-syzygy is shortened with respect to the previously computed mean value of 205.892318 mean solar days. This conforms with the observed facts (see table 17).

It is also important to note that, for reasons explained in chapter 6, once the position of perigee-syzygy occurs with a minimum separation in time between the two components, it may be accompanied in immediately preceding or following months by similarly close, but gradually diverging, perigee-syzygy alignments. These will, as a rule, take the form of wider spaced perigee-syzygy or pseudo-perigee-syzygy situations.

It has been established above that, subject to an assumed constant angular speed of separation, a period of 411.78462 days is required for the position of perigee, continuously falling behind the position of conjunction, to complete a full revolution of 360° around the lunar orbit. At the end of this period, any previously existing coincidence between perigee and conjunction will repeat itself again, but will not usually occur a second time in succession according to this exact time interval. Because there are numerous disturbing influences affecting the Moon's orbital motion, the immediate repetition of this cyclical period will usually be broken.

Short-Period Cycles of Repetition of Perigean Spring Tides

It is obvious that, from the standpoint of winter storms, the greatest astronomically induced potential for tidal flooding will exist in those years in which the calendar arrangement of near-coincidences between perigee and syzyzy permits the greatest number to occur within the most common period of winter storms from November 1 to April 1.

The exact number of occurrences of perigean spring tides in any one year (3–5 having a perigee-syzygy separation-interval of $\pm 24^h$) is a function of the number of close alignments between perigee and syzygy in that calendar year. The number of these close alignments is, in turn, a function of the slow but continuous revolution of the line of apsides (connecting the positions of perigee and apogee) around the Earth in a period of 3,231 days (8.85 years). Other controlling factors include the Moon's revolution around the Earth from perigee to perigee in a period of 27.554550 days, the lunar revolution from new moon to new moon in 29.530588 days, the apparent motion of the Sun around the Earth in an ordinary (tropical) year of 365.242199 days, and certain additional astronomical variables. The numerical interrelationships between these various periods determine the frequency of occurrence of the different classifications of perigee-syzygy alignments.

As the result of the relative movements of the Earth, Moon, and Sun, the repetition of tides of similar phase and amplitude—including those of perigean spring origin—takes place in certain well-defined periods averaging 28.981403, 162.502866, 191.484268, 355.022184, and 384.003587 days,[b] as well as in the previously discussed astronomical cycle of 205.892318 days representing the average motion of perigee around the Earth. Various combinations of these cycles also occur (e.g., 28.981403 +162.502866=191.484269 days). The 205.892318-day cycle is the principal one affecting perigean spring tides; the others are subordinate.

As has been evidenced in chapter 6, a considerable deviation is present between the lengths of the actual and mean values of both the anomalistic and synodic months in those months containing a close perigee-syzygy alignment. The magnitude of this deviation increases as the separation-interval becomes smaller. Accordingly, any assumed value involving an average period of time between perigean spring tides also will least adequately represent the actual period between these tides when the perigee-syzygy alignments are especially close. The deviation from a mean period also will be the greatest, percentagewise, over short periods of time (e.g., one recurring cycle). Over longer periods, the effect of individual variations will more nearly average out, and a comparison of the actual and the mean intervals of time between perigee-syzygy alignments will show smaller residuals. The assumed periodic relationships will, for the same reason, more nearly apply.

Thus, the mean epoch of the proxigee-syzygy alignment of 1974 January 8.49 (e.t.), is connected through the 205.89-day perigee cycle (2×205.89=411.78 days) with a proxigean spring tide occurring on 1972 November 20.98(e.t.) (a Julian Day difference, at mean syzygy, of dt=413.40). In the chain of cyclical interrelationships, the January 8.49 date is also directly related through the 205.89-day cycle (21×205.89=4,323.7 days) with another proxigean spring tide associated with the proxigee of 1962 March 6.375 (e.t.) (dt=4,326.2), in which the extraordinary high waters were further augmented by an intense, wind-driven storm surge to produce extensive flooding along the mid-Atlantic coast (see item 4, later in this chapter).

The 1972 November 20.98 proxigee-syzygy date likewise forms an integral number of multiples of 205.89 (15×205.89=3,088.4 days) with a close perigean spring situation on 1964 June 10.08 (e.t.) (dt=3,086.0 days).

Coastal flooding associated with perigean spring tides occurred at Atlantic City, N.J., on 1967 April 27 and December 3, near the mean perigee-syzygy dates April 24.15 and December 1.13 (e.t.). These dates are separated by a 221.98-day period, which is approximately equivalent to one 191.48- and one 28.98-day cycle (the sum=220.46 days).

Similarly, all four of the previously mentioned perigee-syzygy dates form part of a long-period astronomical relationship extending backward over 31.010 tropical years (11,326 days) or 55 cycles of 205.89 days (11,324 days). These individual perigee-syzygy dates in 1974 are almost exactly repeated at the end of this long cycle, in each case only 2 calendar days after the perigee-syzygy dates which occurred 31 years previously on 1943 January 6, February 4, July 17, and August 15. More will be said concerning this 31-year period in the immediately following section.

Over an even longer period, the four dates of proxigean and perigean spring tides in 1974 also are commensurate with (i.e., an integral number of cycles removed from) proxigean spring tides which were accompanied by severe flooding along the New Jersey coast on 1861 November 2, 113 years earlier (see page 78). The 1861 November 2.69 (G.m.t.) date is separated (dt=40,973.7 days)

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[b] Cf., R. A. Harris, *Manual of Tides,* part V, Currents, Shallow-Water Tides, Meteorological Tides, and Miscellaneous Matters, as Appendix No. 6 in the annual *Report of the Superintendent of the Coast and Geodetic Survey for 1907,* Washington, D.C., U.S. Government Printing Office, 1908, p. 492.

from the 1974 January 8.49, (e.t.) date by 199 cycles of 205.892318 days (total 40,972.6 days).

And, as a final example in this representative list, there are 225 cycles of 162.50 days, plus 3 cycles of 28.98 days (total=36,649.4 days) between the 1861 November 2.69, (G.m.t.) proxigee-syzygy date and that of 1962 March 6.375 (e.t.), accompanied by severe flooding 101 years later (dt=36,647.5 days).

The 31-Year Cycle of Perigee-Syzygy

A very significant relationship exists in the 31-year cycle of iteration which governs close perigee-syzygy alignments. For greater emphasis on the meaning of this relationship in terms of recurrent tidal flooding, the astronomical factors responsible for a periodicity in tidal extremes will be established by an analysis of ephemeris data. This will be followed by correlations between the cyclical data obtained and examples of repeated coastal flooding from past history. Coincidentally, in followup to a previous section, consideration will be given to the unusually hazardous flooding situation which prevails whenever landfalling hurricanes occur on the same dates as those on which markedly elevated perigean tides exist. Because of the inherent danger for extreme coastal flooding produced by the combination of a hurricane plus proxigean or perigean spring tides, this becomes an especially critical aspect in evaluating tidal flooding potential.

It has been established over a long period of record that the month in which the greatest frequency of hurricanes occurs on the Atlantic coast of North America is September. In order to make possible the determination of any desired statistical probability of occurrence incorporating this double threat of hurricanes and high tides, a compilation is included in table 24 of all cases of proxigee-syzygy or perigee-syzygy ($P-S \leq \pm 24^h$) occurring between 1600 and 1999 in the month of September. In consequence of the purely astronomical factors expressed in this table, the augmented tide levels resulting are vulnerable to any type of intense offshore coastal storm occurring in this month. The resulting susceptibilities to tidal flooding apply, therefore, to either hurricanes or winter storms. Although the data are tabulated for the single month of September, the purpose of this tabulation is to discover the cyclical relationships between successive close perigee-syzygy alignments, regardless of their calendar positions. The periodicities revealed may involve any month of the year, depending upon which month is selected as a starting point and whether the repeating cycles are exactly integral ones.

In table 24, col. 1 contains the date of syzygy; col. 2 lists the corresponding Julian Date, including in order that the differences between successive dates of syzygy may be taken over long periods without involving the complexities of calendar months; those successive differences are tabulated in col. 3. Finally, assuming a synodic month having a mean period of 29.530589 days, col. 4 indicates the corresponding number of synodic months represented by the figure in col. 3. Cols. 5, 6, and 7 repeat the same data for the time of perigee. Some interesting facts emerge from the detailed analysis of this table, and the investigation of the anomalistic period is particularly productive.

TABLE 24.—*Short-Term and Long-Term Cyclical Relationships Between Close Perigee-Syzygy Alignments*

Calendar date of syzygy	Julian date of syzygy	Difference between syzygy dates (days)	No. of synodic cycles (to nearest 0.1)	Julian date of perigee*	Difference between perigee dates (days)	No. of anomalistic cycles (to nearest 0.1)
9/ 5/1603	2306791. 2			2306791. 0		
		383. 8	13. 0		384. 8	14. 0
9/23/1604	2307175. 0			2307175. 8		
		1077. 9	36. 5		1076. 2	39. 1
9/ 6/1607	2308252. 9			2308252. 0		
		383. 9	13. 0		384. 9	14. 0
9/24/1608	2308636. 8			2308636. 9		
		1461. 8	49. 5		1461. 1	53. 0
9/24/1612	2310098. 6			2310098. 0		
		1816. 1	61. 5		1817. 3	66. 0
9/15/1617	2311914. 7			2311915. 3		
		1461. 8	49. 5		1461. 2	53. 0
9/15/1621	2313376. 5			2313376. 5		
		1461. 7	49. 5		1460. 9	53. 0
9/16/1625	2314838. 2			2314837. 4		
		1816. 2	61. 5		1817. 5	66. 0

See footnote at end of table.

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TABLE 24.—*Short-Term and Long-Term Cyclical Relationships Between Close Perigee-Syzygy Alignments*—Continued

Calendar date of syzygy	Julian date of syzygy	Difference between syzygy dates (days)	No. of synodic cycles (to nearest 0.1)	Julian date of perigee *	Difference between perigee dates (days)	No. of anomalistic cycles (to nearest 0.1)
9/ 6/1630	2316654. 4			2316654. 9		
		146. 17	49. 5		1461. 0	53. 0
9/ 7/1634	2318116. 1			2318115. 9		
		383. 9	13. 0		384. 8	14. 0
9/26/1635	2318500. 0			2318500. 7		
		1077. 9	36. 5		1076. 3	39. 1
9/ 8/1638	2319577. 9			2319577. 0		
		383. 9	13. 0		384. 0	14. 0
9/27/1639	2319961. 8			2319961. 8		
		1461. 8	49. 5		1461. 2	53. 0
9/27/1643	2321423. 6			2321423. 0		
		1861. 1	61. 5		1817. 3	66. 0
9/17/1648	2323239. 7			2323240. 3		
		1461. 8	49. 5		1461. 1	53. 0
9/17/1652	2324701. 5			2324701. 4		
		1461. 7	49. 5		1461. 0	53. 0
9/18/1656	2326163. 2			2326162. 4		
		1816. 1	61. 5		1817. 3	66. 0
9/ 8/1661	2327979. 3			2327979. 7		
		1461. 8	49. 5		1461. 9	53. 0
9/ 9/1665	2329441. 1			2329440. 9		
		383. 9	13. 0		384. 8	14. 0
9/28/1666	2329825. 0			2329825. 7		
		1077. 9	36. 5		1076. 2	39. 1
9/10/1669	2330902. 9			2330901. 9		
		383. 9	13. 0		384. 9	14. 0
9/29/1670	2331286. 8			2331286. 8		
		1461. 7	49. 5		1461. 1	53. 0
9/29/1674	2332748. 5			2332747. 9		
		1432. 3	48. 5		1432. 6	52. 0
9/ 1/1678	2334180. 8			2334180. 5		
		383. 9	13. 0		384. 7	14. 0
9/20/1679	2334564. 7			2334565. 2		
		1461. 7	49. 5		1461. 1	53. 0
9/20/1683	2336026. 4			2336026. 3		
		1461. 8	49. 5		1461. 1	53. 0
9/21/1687	2337488. 2			2337487. 4		
		1816. 1	61. 5		1817. 3	66. 0
9/10/1692	2339304. 3			2339304. 7		
		1461. 8	49. 5		1461. 1	53. 0
9/11/1696	2340766. 1			2340765. 8		
		383. 9	13. 0		384. 8	14. 0
9/30/1697	2341150. 0			2341150. 6		
		1432. 2	48. 5		1432. 6	52. 0
9/ 2/1701	2342582. 2			2342583. 2		
		1461. 8	49. 5		1461. 1	53. 0
9/ 3/1705	2344044. 0			2344044. 3		
		1461. 8	49. 5		1461. 1	53. 0
9/ 4/1709	2345505. 8			2345505. 4		
		383. 9	13. 0		384. 8	14. 0
9/23/1710	2345889. 7			2345890. 2		
		1461. 7	49. 5		1461. 1	53. 0
9/23/1714	2347351. 4			2347351. 3		
		1461. 8	49. 5		1461. 1	53. 0
9/24/1718	2348813. 2			2348812. 4		
		1816. 1	61. 5		1817. 3	66. 0
9/14/1723	2350629. 3			2350629. 7		
		1461. 8	49. 5		1461. 1	53. 0

See footnote at end of table.

TABLE 24.—*Short-Term and Long-Term Cyclical Relationships Between Close Perigee-Syzygy Alignments*—Continued

Calendar date of syzygy	Julian date of syzygy	Difference between syzygy dates (days)	No. of synodic cycles (to nearest 0.1)	Julian date of perigee*	Difference between perigee dates (days)	No. of anomalistic cycles (to nearest 0.1)
9/15/1727	2352091. 1			2352090. 8		
		1816. 1	61. 5		1817. 4	66. 0
9/ 4/1732	2353907. 2			2353908. 2		
		1461. 8	49. 5		1461. 0	53. 0
9/ 5/1736	2355369. 0			2355369. 2		
		1461. 7	49. 5		1461. 1	53. 0
9/ 6/1740	2356830. 7			2356830. 3		
		383. 9	13. 0		384. 8	14. 0
9/25/1741	2357214. 6			2357215. 1		
		1461. 8	49. 5		1461. 1	53. 0
9/25/1745	2358676. 4			2358676. 2		
		1461. 8	49. 5		1461. 1	53. 0
9/26/1749	2360138. 2			2360137. 3		
		1816. 1	61. 5		1817. 3	66. 0
9/16/1754	2361954. 3			2361954. 6		
		1461. 8	49. 5		1461. 2	53. 0
9/17/1758	2363416. 1			2363415. 8		
		1816. 1	61. 5		1817. 3	66. 0
9/ 7/1763	2365232. 2			2365233. 1		
		1461. 8	49. 5		1461. 1	53. 0
9/ 8/1767	2366694. 0			2366694. 2		
		1461. 7	49. 5		1461. 0	53. 0
9/ 9/1771	2368155. 7			2368155. 2		
		383. 9	13. 0		384. 8	14. 0
9/27/1772	2368539. 6			2368540. 0		
		1461. 8	49. 5		1461. 2	53. 0
9/27/1776	2370001. 4			2370001. 2		
		1461. 7	49. 5		1461. 0	53. 0
9/28/1780	2371463. 1			2371462. 2		
		1816. 2	61. 5		1817. 4	66. 0
9/18/1785	2373279. 3			2373279. 6		
		1461. 7	49. 5		1461. 1	53. 0
9/19/1789	2374741. 0			2374740. 7		
		1816. 2	61. 5		1817. 4	66. 0
9/ 9/1794	2376557. 2			2376558. 1		
		1461. 7	49. 5		1461. 0	53. 0
9/10/1798	2378018. 9			2378019. 1		
		1461. 8	49. 5		1461. 1	53. 0
9/11/1802	2379480. 7			2379480. 2		
		1816. 1	61. 5		1817. 4	66. 0
9/ 2/1807	2381296. 8			2381297. 6		
		1461. 8	49. 5		1461. 0	53. 0
9/ 2/1811	2382758. 6			2382758. 6		
		383. 9	13. 0		384. 9	14. 0
9/21/1812	2383142. 5			2383143. 5		
		1077. 9	36. 5		1076. 3	39. 1
9/ 3/1815	2384220. 4			2384219. 8		
		383. 9	13. 0		384. 5	14. 0
9/21/1816	2384604. 3			2384604. 3		
		1461. 7	49. 5		1461. 3	53. 0
9/22/1820	2386066. 0			2386065. 6		
		1816. 1	61. 5		1817. 4	66. 0
9/12/1825	2387882. 1			2387883. 0		
		1461. 8	49. 5		1461. 0	53. 0
9/13/1829	2389343. 9			2389344. 1		
		1461. 8	49. 5		1461. 1	53. 0
9/13/1833	2390805. 7			2390805. 2		
		1816. 1	61. 5		1817. 3	66. 0

See footnote at end of table.

TABLE 24.—*Short-Term and Long-Term Cyclical Relationships Between Close Perigee-Syzygy Alignments*—Continued

Calendar date of syzygy	Julian date of syzygy	Difference between syzygy dates (days)	No. of synodic cycles (to nearest 0.1)	Julian date of perigee*	Difference between perigee dates (days)	No. of anomalistic cycles (to nearest 0.1)
9/ 4/1838	2392621. 8			2392622. 5		
		1461. 8	49. 5		1461. 1	53. 0
9/ 4/1842	2394083. 6			2394083. 6		
		383. 9	13. 0		384. 9	14. 0
9/23/1843	2394467. 5			2394468. 5		
		1077. 8	36. 5		1076. 1	39. 1
9/ 5/1846	2395545. 3			2395544. 6		
		383. 9	13. 0		384. 9	14. 0
9/24/1847	2395929. 2			2395929. 5		
		1461. 8	49. 5		1461. 1	53. 0
9/25/1851	2397391. 0			2397390. 6		
		1816. 1	61. 5		1817. 3	66. 0
9/14/1856	2399207. 1			2399207. 9		
		1461. 8	49. 5		1461. 1	53. 0
9/15/1860	2400668. 9			2400669. 0		
		1461. 8	49. 5		1461. 2	53. 0
9/15/1864	2402130. 7			2402130. 2		
		1816. 1	61. 5		1817. 3	66. 0
9/ 6/1869	2403946. 8			2403947. 5		
		1461. 8	49. 5		1461. 1	53. 0
9/ 6/1873	2405408. 6			2405408. 6		
		383. 9	13. 0		384. 8	14. 0
9/25/1874	2405792. 5			2405793. 4		
		1077. 8	36. 5		1075. 9	39. 0
9/ 7/1877	2406870. 3			2406869. 3		
		383. 9	13. 0		385. 2	14. 0
9/26/1878	2407254. 2			2407254. 5		
		1461. 8	49. 5		1461. 1	53. 0
9/27/1882	2408716. 0			2408715. 6		
		1816. 1	61. 5		1817. 3	66. 0
9/17/1887	2410532. 1			2410532. 9		
		1461. 8	49. 5		1461. 1	53. 0
9/18/1891	2411993. 9			2411994. 0		
		1461. 7	49. 5		1461. 1	53. 0
9/18/1895	2413455. 6			2413455. 1		
		1816. 0	61. 5		1815. 9	65. 9
9/ 9/1900	2415271. 6			2415271. 0		
		1461. 9	49. 5		1462. 5	53. 1
9/ 9/1904	2416733. 5			2416733. 5		
		383. 9	13. 0		384. 8	14. 0
9/28/1905	2417117. 4			2417118. 3		
		1077. 9	36. 5		1076. 2	39. 1
9/10/1908	2418195. 3			2418194. 5		
		383. 9	13. 0		384. 9	14. 0
9/29/1909	2418579. 2			2418579. 4		
		1461. 8	49. 5		1461. 1	53. 0
9/30/1913	2420041. 0			2420040. 5		
		1432. 2	48. 5		1432. 5	52. 0
9/ 1/1917	2421473. 2			2421473. 0		
		383. 9	13. 0		384. 9	14. 0
9/20/1918	2421857. 1			2421857. 9		
		1077. 9	36. 5		1076. 2	39. 1
9/ 2/1921	2422935. 0			2422934. 1		
		383. 9	13. 0		384. 9	14. 0
9/21/1922	2423318. 9			2423319. 0		
		1461. 7	49. 5		1461. 0	53. 0
9/21/1926	2424780. 6			2424780. 0		
		1816. 2	61. 5		1817. 4	66. 0

See footnote at end of table.

TABLE 24.—*Short-Term and Long-Term Cyclical Relationships Between Close Perigee-Syzygy Alignments*—Continued

Calendar date of syzygy	Julian date of syzygy	Difference between syzygy dates (days)	No. of synodic cycles (to nearest 0.1)	Julian date of perigee*	Difference between perigee dates (days)	No. of anomalistic cycles (to nearest 0.1)
9/12/1931	2426596. 8			2426597. 4		
		1461. 7	49. 5		1461. 1	53. 0
9/12/1935	2428058. 5			2428058. 5		
		383. 9	13. 0		384. 7	14. 0
9/30/1936	2428442. 4			2428443. 2		
		1077. 9	36. 5		1076. 3	39. 1
9/13/1939	2429520. 3			2429519. 5		
		1816. 1	61. 5		1817. 4	66. 0
9/ 2/1944	2431336. 4			2431336. 9		
		1461. 8	49. 5		1461. 1	53. 0
9/ 3/1948	2432798. 2			2432798. 0		
		383. 9	13. 0		384. 8	14. 0
9/22/1949	2433182. 1			2433182. 8		
		1077. 8	36. 5		1076. 2	39. 1
9/ 4/1952	2434259. 9			2434259. 0		
		383. 9	13. 0		384. 8	14. 0
9/23/1953	2434643. 8			2434643. 8		
		1461. 8	49. 5		1461. 2	53. 0
9/23/1957	2436105. 6			2436105. 0		
		1816. 1	61. 5		1817. 3	66. 0
9/14/1962	2437921. 7			2437922. 3		
		1461. 8	49. 5		1461. 1	53. 0
9/14/1966	2439383. 5			2439383. 4		
		1461. 8	49. 5		1461. 1	53. 0
9/15/1970	2440845. 3			2440844. 5		
		1816. 1	61. 5		1817. 3	66. 0
9/15/1975	2442661. 4			2442661. 8		
		1461. 8	49. 5		1461. 2	53. 0
9/ 6/1979	2444123. 1			2444123. 0		
		383. 9	13. 0		384. 8	14. 0
9/24/1980	2444507. 1			2444507. 8		
		1077. 8	36. 5		1076. 1	39. 1
9/ 7/1983	2445584. 9			2445583. 9		
		383. 9	13. 0		384. 9	14. 0
9/25/1984	2445968. 8			2445968. 8		
		1461. 8	49. 5		1461. 1	53. 0
9/25/1988	2447430. 6			2447429. 9		
		1816. 1	61. 5		1817. 3	66. 0
9/16/1993	2449246. 7			2449247. 2		
		1461. 8	49. 5		1461. 2	53. 0
9/16/1997	2450708. 5			2450708. 4		

**Note:* It has been seen (part II, chapters 3, 4) that certain lunar perturbations are especially critical at times of perigee-syzygy. During the early course of the research for this project, it was discovered that the utilization of a substantial and presumably quite sufficient number of reduction terms among the theoretical expressions for solution of the Moon's orbital position and motion was still quantitatively inadequate. The insufficiency lay in the determination of geocentric horizontal parallax and the times of perigee and syzygy to the accuracy required for consistency with ephemeris data.

A corresponding computer reprogramming was introduced, expanding from the partial sequence of analytic terms in table 16A to the full complement of terms given in table 16B. All tables in this monograph involving lunar positions and motions—including the data displayed in the computer printout of table 16—are now based either upon the full reduction expressions contained in table 16B, or upon *The American Ephemeris and Nautical Almanac*.

However, table 24 already had been typeset from data computed on the basis of the initial, smaller number of analytic terms. The time differences, perigee minus syzygy, may occasionally vary from 1–3 hours between the solutional accuracies of the short and long methods, if the individual differences are additive in the same direction. Thus the Julian dates of perigee in table 24 (which, as throughout this work, are represented as a function of their intervals from syzygy) may, in some few cases, differ by 0.1–0.2^d from the more precise data obtainable from table 16. Because such slight differences do not materially affect the average values of the long-range cycles of recurrence of perigee-syzygy listed in table 24, these original values calculated from a smaller number of analytic terms have not been altered. The periodic relationships present are quite readily apparent.

The various repeating cycles of anomalistic months between successive perigee-syzygy dates as given in col. 7 are: 14.0, 39.1, (52.0 or 53.0), and 66.0. Assigning each cycle a serial number in this same sequential order it is obvious that, with some few interruptions and irregularities (i.e., wherever 52 instead of 53 cycles occur), the two principal cycles which are systematically repeated are 1–3–3–4–3–4–3–3 and 1–3–4–3–3–4–3–1–2.

Adding the total number of cycles contained in each of these repeating series gives 411.0 and 411.1 anomalistic months, respectively. The average between these two values is equivalent to 11,326 mean solar days or 31.010 tropical years. As noted in the preceding section, this is also very nearly equivalent (11,324 days) to 55 cycles of the 205.89-day average period between ordinary perigee-syzygy alignments.

Using this 31-year cycle, it is now possible to establish an interesting relationship connecting several of the very major tidal floodings on the east coast of North America (see table 1) which have occurred at times of large parallax (π) and close perigee-syzygy separations (P–S). These cases are starred in the list below.

TABLE 25.—*Cases of Extreme Tidal Flooding Coinciding With Long-Term Astronomical Cycles of Close Alignment Between Perigee and Syzygy*

Lunar Phase	Date (G.c.t.)	π (at proxigee)	$\delta☾$ °	P−S h
NM	1776 Feb. 19 . . .	61′26.4″	−12.0	+4
FM	1807 Feb. 22 . . .	61′30.2″	+5.2	+2
NM	1838 Feb. 24 . . .	61′27.1″	−12.0	+2
FM☆	1869 Feb. 26 . . .	61′28.7″	+10.1	+1
NM☆	1900 Mar. 1 . . .	61′28.2″	−2.9	+1
FM★	1931 Mar. 4 . . .	61′29.0″	+9.3	−1
NM★	1962 Mar. 6 . . .	61′26.6″	−8.2	0
FM	1993 Mar. 8 . . .	61′30.1″	+0.6	−2

It will be observed that all of the above are cases of astronomical proxigee-syzygy (and hence associated with proxigean spring tides) according to the parallax limits of ≧61′26.5″ to <61′29.0″ previously defined. (Strictly speaking, the first example is but negligibly below this range; the second and the last are, in fact, well into the extreme proxigee-syzygy range.) All have very low P−S values, and these are seen to converge to a minimum at the time of the great 1962 flooding event. The slight excess in period over an exact 31 years is responsible for the systematic forward sliding of 2–3 days between cycles. The alternation in lunar phase from new moon to full moon and in declination from positive to negative values between successive cycles should also be noted.

The two cases of proxigee-syzygy marked with a solid star (★) were both accompanied by severe tidal flooding (see table 1). A slightly different situation exists for the two cases identified by an open star (☆): The great coastal flooding of 1869 Oct. 5 in New Brunswick, Canada (see page 112), was associated with a perigee-syzygy alignment on this same date (π_{max}=61′24′4″, P−S=−7^h). However, the flooding occurred at the end of a 221.5-day interval (194.0^d+27.5^d) following the 1869 Feb. 26 date listed in the above table. This is equivalent to the normal period (7.5 months of 29.5^d) between successive perigee-syzygy alignments possessing the smallest P−S intervals in any one lunar year (see fn. p. 177). Obviously, therefore, this case was paired with the February 26 date in the same 31-year cyclical relationship responsible for a very close proxigee-syzygy alignment and large parallax. In the same manner, the major tidal flooding of 1900 Oct. 11–12 (maximum π =61′26.1″. P−S=−7^h on Oct. 8) occurred 221.5 days after the closest P−S alignment in the year on 1900 Mar. 1 as listed in table 25. Exactly the same reasoning applies to the influence of the 31-year cycle upon the 1900 Oct. 11–12 flooding. To date, flooding events have not been discovered which are related to the 1776, 1807, and 1838 dates.

Attention is drawn to the near-equatorial position of Sun and Moon, the large lunar parallax, and the classification of the astronomical circumstance as one of extreme proxigee-syzygy on 1993 Mar. 8, should meteorological conditions supporting tidal flooding prevail within a period of several days on either side of this date in lowland coastal regions. This date is the next 31-year multiple following the 1962 Mar. 6 coastal flooding catastrophe on the mid-Atlantic coast.

Meteorological Aspects of Coastal Flooding at Times of Perigean Spring Tides

It has been stated repeatedly throughout this work that perigean spring tides alone are not sufficient to cause major coastal flooding, but must be accompanied at the times of attaining one or more of their successive peaks of astronomical high water by strong, persistent, onshore winds.

It is in no way the intention of the present volume to enter into a detailed discussion of the nature of the meteorological factors contributing to each of the coastal flooding events enumerated in table 1. This would require another volume of equal length, and representative descriptions of the meteorological circumstances accompanying specific cases of coastal flooding attributed to "storm tides" or "storm surges" are already available in the scientific literature (see bibliography—categories 18 and 42).

It would, however, be remiss to conclude the present study without providing the meteorological conditions acting on the tides in a representative group of coastal flooding events. To provide a suitable comparison, these should be chosen chronologically and at random (see the Explanatory Comments preceding figures 50–69) from the total number of cases in table 1. Such a purely representative documentation of the state of the weather accompanying cases of major coastal flooding which have occurred at the times of perigean spring tides is contained in the following pages.

Surface synoptic weather maps prepared by the U.S. Weather Bureau (now the National Weather Service), meteorological and climatological records, cloud-cover photographs taken from artificial satellites, and other data concurrent with these coastal flooding events are variously presented for comparison with the flooding data.

According to this plan, the surface synoptic weather maps most closely accompanying each of 20 cases of major tidal flooding occurring at times of perigean spring tides are grouped together in succeeding pages of the present chapter (see table 26). To provide an effective balance, these are followed by the synoptic weather maps for 20 cases of nonflooding which accompanied instances of very close alignment of perigee-syzygy, but in which the necessary strong, persistent, onshore winds to support the augmented astronomical high tide were lacking (see table 27). Tables 28a–28b list, respectively, representative cases of (1) hurricanes concurrent with perigean spring tides and (2) impairment of hydrological runoff by such tides.

There ensues a text discussion of an additional eight cases of perigean/proxigean spring tides deserving of special attention because of the special circumstances thereof and/or the very severe degree of accompanying tidal flooding. (Table 29 lists the synoptic weather maps provided for four of these cases.) Certain supplementary newspaper accounts and quoted excerpts from report literature are also presented for their topical value. Among other data included for these special instances of tidal flooding described in the text are the following: A curve plot showing the predicted rate of tide growth subject to astronomical causes at the time of the 1931 March 4–5 tidal flooding is introduced as a basis for further interpretation in chapter 8. Curves showing the actual rate of tide growth subject to the combined effect of astronomical causes, plus wind, have been prepared for the 1962 March 6–7 tidal flooding event. Finally, aerial and ground photographs of the extent of structural and erosional damage resulting from various of the most recent of these coastal flooding events along the North American coastline are included.

It must be brought out in the latter connection that restrictions to photography—even from the air—are often imposed by the combination of the ocean waters intruding over the land, strong and gusty winds, a turbulent atmosphere, intense precipitation and/or dark, heavy, and low cloud cover generally associated with such storm-assisted tidal flooding events. Hence any closeup film documentation of the flooding effects often is not possible until the seawater has receded from the land, and meteorological conditions permit detailed photography. The photographs of final destruction caused, taken after the waters subside, do not in any sense reflect the total chaos nor the violent conditions prevalent during the actual period of flooding from the sea.

Selection of Multidisciplinary Data Sources

Because of the tremendous amount of information researched and the profusion of data reduced and made available for graphic presentation, a concept of diversification becomes the most logical selection principle in providing a balanced representation of such data suitable for interdisciplinary comparison.

Seven of the lettered weather maps corresponding to dates of perigean spring tides, for which news accounts of the accompanying coastal flooding are provided (see table 5), and for which rate-of-tide-rise curves also have been computed (see chapter 8), are among the cases listed in table 26. These cases, which permit a full intercomparison of data, comprise a part of the first series of weather maps, arranged in chronological order. The specific cases involved are A–43, B–50, C–51, F–68, G–69, H–72, and I–83e. One case (M–98e,w) includes both a weather map and two individual tide curves, but has no accompanying printed news articles. An additional seven cases among this first group of weather maps are represented by news summaries of the associated severe tidal flooding but, because of space limitations, do not possess matching tide curves. These cases are 25, 34, 35, 63, 64, 74, and 94.

Five cases of coastal flooding (I–83e, J–85, 86, M–98w, and N–99) for which tide curves as well as daily weather maps and published newspaper reports relative to the flooding are provided in this work—and two (F–68 and O–100), supplemented by newspaper excerpts but no tide curves—appear separately in this chapter, where a detailed discussion of these major tidal flooding events is presented. Tide curves for other outstanding examples of coastal flooding (D–57 and E–58) for which news accounts are available—but this time with the omission of the full-page weather maps—are also included in chapter 8. Both a weather map and tide curves are published for K–87 in the text, but because of the widely scattered and unusual nature of this event, U.S. Weather Bureau sources are used, and news articles are not included in table 5. Satellite cloud-cover photographs taken by night-infrared and day-infrared cameras are also provided for event N–99.

The Correlation of Meteorological and Astronomical Data

As has been noted in both the first and present chapters of this work, meteorological factors may act either to support, or to reduce, the effects of astronomically induced tides. Because of the large area of coastal coverage, provided by synoptic weather maps, including the adjoining oceans and ship weather reports, these offer the most convenient means of determining both the continental and marine pressure and wind patterns in existence at the time of perigean spring tide. The daily synoptic weather maps of the United States used as data sources throughout this work are copies of those compiled and published by the U.S. Weather Bureau (since October 3, 1970, the National Weather Service) as a part of its forecasting analysis and historical record series. The oversize printed maps in all cases have been photographically reduced, and appropriate overlays and spellouts have been applied to emphasize the critical factors of wind direction and velocity (and the movement of relevant low pressure atmospheric pressure systems) as these variously affect the potential for tidal flooding in connection with perigean spring tides.

GROUPING OF THE WEATHER MAPS

The series of synoptic weather maps contained on the following pages consists of four distinct sections, within each of which the maps are chronologically arranged:

(a) The first section consists of 20 weather maps showing—as closely as can be correlated—the meteorological conditions accompanying a randomly selected group of examples of major tidal flooding. These were observed along either the east or west coasts of North America (or on both coasts, simultaneously). Each such instance of coastal flooding represented was associated with the perigean spring tides which occurred on, or very near to, the date of one of these weather maps.

The group of weather maps contained in table 26 therefore involves actual coastal flooding events in which (1) close perigee-syzygy alignments (and resulting perigean spring tides) as well as (2) strong, sustained, onshore winds (usually generated by offshore low pressure centers) joined to become the cause of coastal flooding. As in all examples used, the incidents of tidal flooding were selected, without any systematic predetermination, from the catalog of 100 such representative events compiled in part I, table 1 of chapter 1.

(b) A second, control group of 20 weather maps in table 27, chosen with equal randomness in each decade throughout the same 90-year period, show the meteorological conditions at times of extreme close perigee-syzygy alignments. The factors producing perigean spring tides also were selected to include a variety of solar and lunar positional relationships representative of significant tide-amplifying forces and inequalities, as described in chapter 5. These different circumstances are listed in the "Remarks" column of the table. The resulting astronomical tides were, as in the first series of examples, raised to unusual levels, but no pronounced flooding was observed in these cases, due to the complete absence of persistent, strong, onshore winds at the time.

The weather situations portrayed in this category are generally dominated by large high pressure systems, in which wind conditions ranging from light and variable breezes to a complete calm are common. The associated high barometric pressure and/or offshore winds are both counterproductive to the generation of additionally augmented and flood-producing high tides.

(c) Although, for reasons given in part I, chapter 1, the consideration of coastal flooding resulting from the impact of hurricanes does not form a major part of the present investigation, a few appropriate weather maps depicting conditions in which hurricanes have quite closely coincided with perigean spring tides are included in table 28a.

Together with the accompanying explanation in the text of the present chapter, these examples will help to substantiate the role of perigean spring tides, when acted upon by the onshore winds of a hurricane. The result is, by comparison, a much greater amount of water damage through tide-supported flooding—in addition to the hurricane-induced wind damage—whenever such hurricanes occur near the times of perigean spring tides.

In an example at the opposite end of the scale, a typical case is also included in table 28b in which the unusually high waters associated with perigean spring tides—because of the influence of strong, onshore winds—became a major factor in blocking hydrological runoff. Quite numerous instances exist in which exceptional perigean spring tides (even *without* the support of onshore winds) have, through such blocking action, variously caused, contributed to, or severely aggravated coastal flooding associated with surface runoff of heavy rainfall—or melting ice and snow. A number of such examples are considered in the text.

(d) Finally, a special series of eight weather maps representing, like those in table 26, cases in which perigean spring tides accompanied by strong, persistent, onshore winds have caused prominent coastal flooding, are listed in table 29. Together with four other examples of major tidal flooding, they are of sufficient importance or uniqueness to be discussed individually in the text of this chapter.

Tables 26–29 thus list the weather maps available in each of the above four groups. Immediately following the present discussion, a set of Explanatory Comments is provided summarizing the various symbols, descriptors, and technical data used on these synoptic weather charts. To determine the full implication of all meteorological factors, reference also should be made to the text and cross-related graphic materials of this and other chapters for the following pertinent topics: (a) the practical effects of strong, sustained, onshore winds in driving the amplified waters of perigean spring tides onto the coastline (chapter 7); (b) the value of coordination and intercomparison of these weather maps with the computed rate-of-growth tide curves illustrating the astronomically induced, rapid rise in water level at time of perigee-syzygy which provides a natural setup condition for wind-actuated onshore flooding (chapter 8); and (c) the possibility of assessing and grading the violence of the coastal flooding resulting from the combination of perigean spring tides and onshore winds by means of contemporary newspaper accounts of the damage produced, as given in table 5 (part I, chapter 1).

EXPLANATORY COMMENTS CONCERNING THE MANNER OF DESIGNATION OF WEATHER MAPS AND THE CONCURRENT PERIGEE-SYZYGY DATA

The number in the upper left-hand corner of each weather map is a serial number for ease in chronological comparison and evaluation of these maps. All maps contain such a serial number. In addition, some of the weather maps are designated by a capital-letter prefix. This is a key letter, to allow a ready intercomparison of a variety of data—in some cases located at different places in the book—but all pertaining to the same example of tidal flooding. Only significant cases of tidal flooding which are the subject of detailed investigation in the present work are designated by a key letter. In this system of computation of standard comparative data for master cases, one such example of coastal flooding associated with perigean spring tides has been chosen, at random, in each decade from 1910 (at which time 37 harmonic components replaced the previous 19 in Coast and Geodetic Survey tidal computations) down to 1970. These sample cases have purposely been selected on both coastlines of North America, representing both semidiurnal and mixed tides, and distributed throughout a wide range of latitudes as well as varying astronomical, hydrographic, climatological, and meteorological conditions.

Appropriate tide curves based on predicted tide heights at appropriate nearby tidal *reference stations,* and showing the accelerated rate of tide growth subject to the influence of perigee-syzygy, have been prepared in figs. 153–163 (table 33) for 16 prototype examples of tidal flooding. These are presented, together with an appropriate discussion thereon, in chapter 8.

The corresponding daily synoptic weather map for many of these cases is included in a grouped series of maps following these comments (table 26), or may individually accompany the detailed discussion of representative examples of major tidal flooding contained in the text of this chapter (table 29). In addition, a compilation of newspaper articles covering 50 of the 100 representative cases of major tidal flooding itemized in table 1 graphically describes the extent of the coastal flooding occurring in conjunction with these various cases of perigean spring tides. The latter compilation comprises table 5 of part I, chapter 1.

The procedure previously mentioned—involving a random sampling of the tremendous quantities of meteorological and tidal data available—makes practicable a coordinated investigation of the various related, interdisciplinary factors which enter into such cases of tidal flooding. This analysis is expedited through the intercomparison of those various sources of data which, because of their common relationship in time, bear the same alphanumeric designation in the various index lists (tables 1–5, 26, 27, 28a,b, 29, 33).

The first date given (in roman type) in the upper right-hand corner of each weather map is the date of the weather map; each map has been chosen to accord as nearly as possible with the date on which coastal flooding occurred. The calendar date is immediately followed by the eastern standard time (e.s.t.) for which the weather map is plotted. [Subtract 3 hours to obtain Pacific standard time (P.s.t.) for cases of flooding on the west coast; Greenwich civil time (G.c.t.) may be obtained by adding 5 hours to e.s.t.]

The second entry (in italics) gives the date and time (e.s.t.) of mean perigee-syzygy; this mean epoch of perigee-syzygy for any occurrence is obtained by taking half the difference between the respective times of perigee and syzygy—in the sense perigee minus syzygy—and adding the result algebraically to the time of syzygy. All time values are rounded off to the nearest hour. The last number, in parentheses, gives the algebraic difference in time, in hours, between perigee and syzygy (likewise taken in the sense perigee minus syzygy).

Cases in which the difference in time between perigee and syzygy is less than 24 hours are tabulated in the computer printout (table 16). In this table, the times are given for syzygy (plus an additive or subtractive value, in hours, to give the time of perigee). All times given are in ephemeris time (e.t.)—which corresponds very closely with, and for the present purpose may be assumed to be equal to, Greenwich civil time (G.c.t.). Although the times used (immediately following the date) have been consistently rounded off to the nearest hour, they are sufficiently accurate for reference use in connection with these weather maps.

Wherever the separation-interval between perigee and syzygy is equal to, or greater than 24 hours, the difference has been taken from *The American Ephemeris and Nautical Almanac,* or from astronomical data contained in annual tide tables. All such values are similarly rounded off to the nearest hour, since the time of perigee is now customarily given only to this accuracy. In earlier years, the times of both perigee and syzygy were tabulated to the nearest minute (or tenth of an hour).

The time difference determined by use of any of the previously mentioned publications may vary as much as 2 hours from those (involving cumulative rounding-off procedures) contained in the computer printout. However, any influence of this small rounding-off error is inconsequential for the present use. (It should be noted that, in connection with the curves of rate-of-tide-growth included in chapter 8, the more precise perigee-syzygy values derived from tide tables or *The American Ephemeris and Nautical Almanac* are used without exception.)

All of the weather maps shown were plotted subsequent to the official adoption of standard time in the United States in 1883 and are, therefore, based on the standard time system. Each map is plotted from data consistent in time with that of the standard meridian 75°W., which corresponds to eastern standard time.

The wind velocities indicated by the number of barbs (and flags) on the shafts of the wind arrows extending from each station model must be evaluated according to one of two different systems of symbolic representation. These are shown in the accompanying legends titled "U.S. Weather Map Wind Arrow Symbols" as published in the 1949 and

U. S. WEATHER MAP WIND ARROW SYMBOLS*

BEAUFORT NUMBER	ff	MILES (STATUTE) PER HOUR	KNOTS
0	◎	CALM	CALM
1		1-3	1-3
2		4-7	4-6
3		8-12	7-10
4		13-18	11-16
5		19-24	17-21
6		25-31	22-27
7		32-38	28-33
8		39-46	34-40

BEAUFORT NUMBER	ff	MILES (STATUTE) PER HOUR	KNOTS
9		47-54	41-47
10		55-63	48-55
11		64-72	56-63
12		73-82	64-71
13		83-92	72-80
14		93-103	81-89
15		104-114	90-99
16		115-125	100-108
17		126-136	109-118

LEGEND (ff): ½ FEATHER = 1 BEAUFORT NO. (F). EACH BEAUFORT NO. CORRESPONDS TO THE WINDSPEED RANGE INDICATED (IN STATUTE MILES PER HOUR AND IN KNOTS, OR NAUTICAL MILES PER HOUR). VELOCITY (MPH) = $1.87\sqrt{F^3}$

*Authority: International Meteorological Organization (IMO), Publication No. 9, Fascicule I, Ed. 1949, Chapter III, Suppl. 1, pg. III-3 (1.12) "Wind."

FIGURE 48.—The system of U.S. Weather Map wind arrow symbols in use between January 1, 1949 and January 1, 1955. This symbolic coding system is applicable to the determination of windspeeds and directions on the earlier surface synoptic weather maps which follow. Included among these are both the charts plotted between the preceding two dates and (with esentially the same wind velocity interpretation) those prepared prior to 1949, until the first few of the 19th century charts are considered. (See also the accompanying text under "Explanatory Comments . . .")

1955 editions of the synoptic weather code (figs. 48 and 49). These wind symbols were officially put into use in the United States on January 1, 1949 and January 1, 1955. Subsequent to the 1955 date, the system of wind representation has remained the same; prior to the 1949 date, winds were symbolized essentially according to the procedure indicated in the 1949 code until very early dates are considered. On some of these early weather maps, strong wind velocities are shown by small, solid black squares attached to the shafts of the wind arrows; the squares indicate winds of "cautionary force." On such earlier weather maps, the numbers following the barometric pressure represent the wind speed in miles per hour.

Atmospheric fronts were not introduced on U.S. Weather Bureau synoptic weather maps until August 1, 1941. Before that time, although the common wind shifts across a front were not utilized, the prevailing patterns of highs and lows indicate the direction of surface wind flow (in the Northern Hemisphere, clockwise around a high, counterclockwise around a low).

1. The Tidal Flooding of 1931 March 4–5

The first example (D–57) described among the following individual cases of tidal flooding—that of 1931 March 4–5—occurred at a time when the U.S. Weather Bureau's *Monthly Weather Review*, for logistic reasons, provided only a minimum of offshore and coastal storm information. It also occurred prior to the dates on which were inaugurated the information sources *Climatological Data—National Summary* (with its section on "Severe Storms" begun in January 1950 and changed, in January 1954, to "Storm Data and Unusual Phenomena") or the

U. S. WEATHER MAP WIND ARROW SYMBOLS*

ff	MILES (STATUTE) PER HOUR	KNOTS
	CALM	CALM
	1-4	1-2
	5-8	3-7
	9-14	8-12
	15-20	13-17
	21-25	18-22
	26-31	23-27
	32-37	28-32
	38-43	33-37

ff	MILES (STATUTE) PER HOUR	KNOTS
	44-49	38-42
	50-54	43-47
	55-60	48-52
	61-66	53-57
	67-71	58-62
	72-77	63-67
	78-83	68-72
	84-89	73-77
	119-123	103-107

LEGEND (ff): ½ FEATHER = 5 KNOTS (MEAN WIND SPEED); 1 FEATHER = 10 KNOTS; 1 FLAG = 50 KNOTS.

*Authority: First Session of the Commission for Synoptic Meteorology (CSM-I) April 1953. Recommendation # 42 (Adopted in November 1954 by the U. S.).

FIGURE 49.—The system of U.S. Weather Map wind arrow symbols adopted on January 1, 1955 and in force since that time. Note especially the use of flags to replace feathers at higher windspeeds, and the conversion from miles per hour to knots as the basic unit of windspeed.

TABLE 26.—*Surface Synoptic Weather Maps for Twenty Representative Cases of Coastal Flooding Associated With Perigean Spring Tides and Strong, Sustained, Onshore Winds*

Key letter and serial No.	Weather map date and mean perigee-syzygy date (e.s.t.)		Perigee —syzygy (in hours)	Location of tidal flooding
25	1895 February 8 February 9	8. 0h 10. 0h	(− 4)	Staten Island, N.Y.; Providence, Newport, R.I.; Cape Cod, New Bedford, Boston, Mass.; Bangor, Portland, Bath, Me.
27	1896 November 6 November 4	8. 0h 19. 5h	(−15)	Pictou, Nova Scotia
34	1901 November 24 November 25	8. 0h 15. 5h	(− 9)	Asbury Park, Sea Bright, Keyport, N.J.; Coney Island, N.Y.; New Haven. Stamford, Greenwich, Conn.; Chatham, Provincetown, Mass.
35	1908 February 2 February 2	8. 0h 0. 0h	(− 8)	Port aux Basques, Newfoundland; Harrington Harbour, Quebec
41	1917 October 1 September 30	8. 0h 2. 5h	(−27)	Moncton, Sackville, Amherst Harbor, New Brunswick
A-43	1918 April 10 April 10	8. 0h 14. 5h	(−19)	Sea Bright, Atlantic City, N.J.; Staten Island, Rockaway Beach, southern Long Island, N.Y.
B-50	1927 March 3 March 3	8. 0h 21. 5h	(+15)	New England coast
C-51	1927 April 2 April 1	8. 0h 20. 0h	(− 6)	Atlantic City, N.J.; Delaware
63	1933 December 17 December 17	8. 0h 2. 5h	(+ 9)	Hoquiam, Cosmopolis, Aberdeen, Montesano, Wash.
64	1934 August 21 August 24	8. 0h 3. 0h	(−24)	Balboa, Malibu, Newport, and Laguna Beaches, Calif.
F-68	1939 January 4 January 5	7. 5h 23. 0h	(+14)	Aberdeen, Hoquiam, Neskowin, Wash.; Astoria, Marshfield, Coos Bay, Delake, Oreg.; northern Calif.
G-69	1940 April 21 April 21	7. 5h 7. 0h	(−34)	Boston, Minot's Light, Deer Island, Bassing's Island, Hull, Winthrop, Quincy, Mass.
H-72	1945 November 20 November 19	1. 5h 3. 5h	(−13)	Eastport, Machiasport, Portland, Me.
74	1948 January 26 January 26	1. 5h 4. 0h	(+ 4)	Vicinity of San Francisco, Calif.
I-83e,w	1959 December 29 December 29	1. 0h 5. 0h	(−18)	Atlantic City, N.J.; Long Island, N.Y.; Hull, Boston, Provincetown, Gloucester, Cape Cod, Barnstable, Mass.; Kennebunkport, Me.; San Franciso Bay area, Calif.
84e,w	1961 January 15 January 16	1. 0h 17. 5h	(+ 1)	Atlantic City, N.J.; Delaware; Ventura County, Calif.
86	1962 October 13 October 13	1. 0h 3. 5h	(− 9)	Local estuaries and bay locations, Oreg., Wash., and northern Calif.
L-93e,w	1971 March 26 March 26	7. 0h 9. 0h	(−10)	Vicinity of Sewell's Point, Virginia Beach, Willoughby, Ocean View, Norfolk, Sandbridge, Va.; Oxnard Shores, Calif.
94	1971 April 23 April 24	7. 0h 6. 0h	(−34)	Oxnard Shores, near Oxnard, Calif.
M-98e,w	1973 December 11 December 10	7. 0h 7. 5h	(+21)	Tokeland, Raymond, South Bend, Wash.; Seaside, Astoria, Newport, Oreg.; Halifax, Nova Scotia

full-size monthly report *Storm Data* (initiated January 1959). Thus, detailed technical data concerning this case of coastal flooding are not available. However, the history and course of the atmospheric storm which added its effects to perigean spring tides to produce tidal flooding are included in an article appearing in the *New York Times* for March 5, 1931, which is reproduced, in partly abbreviated form, below. (See figs. 95, 96.)

This example is historically meaningful as an instance of perigean spring tides accompanied by widespread coastal flooding. The March 5 flooding event is of theoretical significance to this study because of its association with astronomical tides predicted to rise (at Boston) 6.3 ft above mean tidal level at this location and, therefore, particularly vulnerable to wind attack. It is technically important because of the extremely close perigee-syzygy alignment which existed on this occasion (see reference note 4 to chapter 4, part II at the end of this volume) and which was responsible for the greatly enhanced astronomical high tides experienced.

As an example, the value of the astronomically produced higher high water predicted for Boston, Mass.

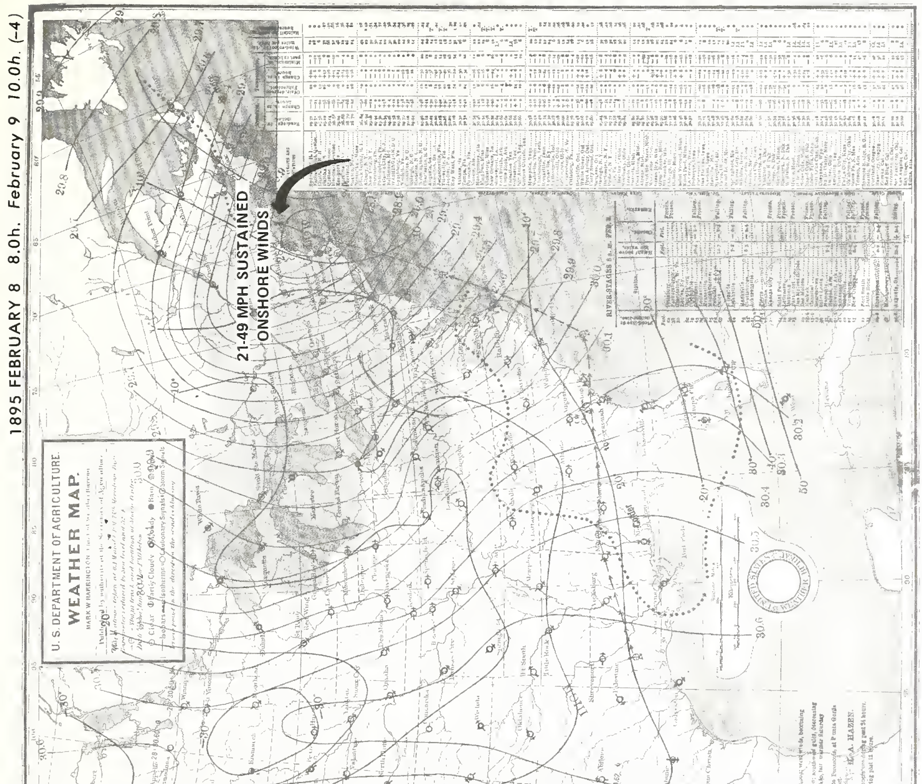

25
1895 FEBRUARY 8 8.0h. February 9 10.0h. (−4)
21-49 MPH SUSTAINED ONSHORE WINDS
VARIABLE WINDS
U. S. DEPARTMENT OF AGRICULTURE.
WEATHER MAP.
Washington, D.C., Friday, February 8, 1895—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
RIVER-STAGES 8 a. m. 75th M.

FIGURE 50

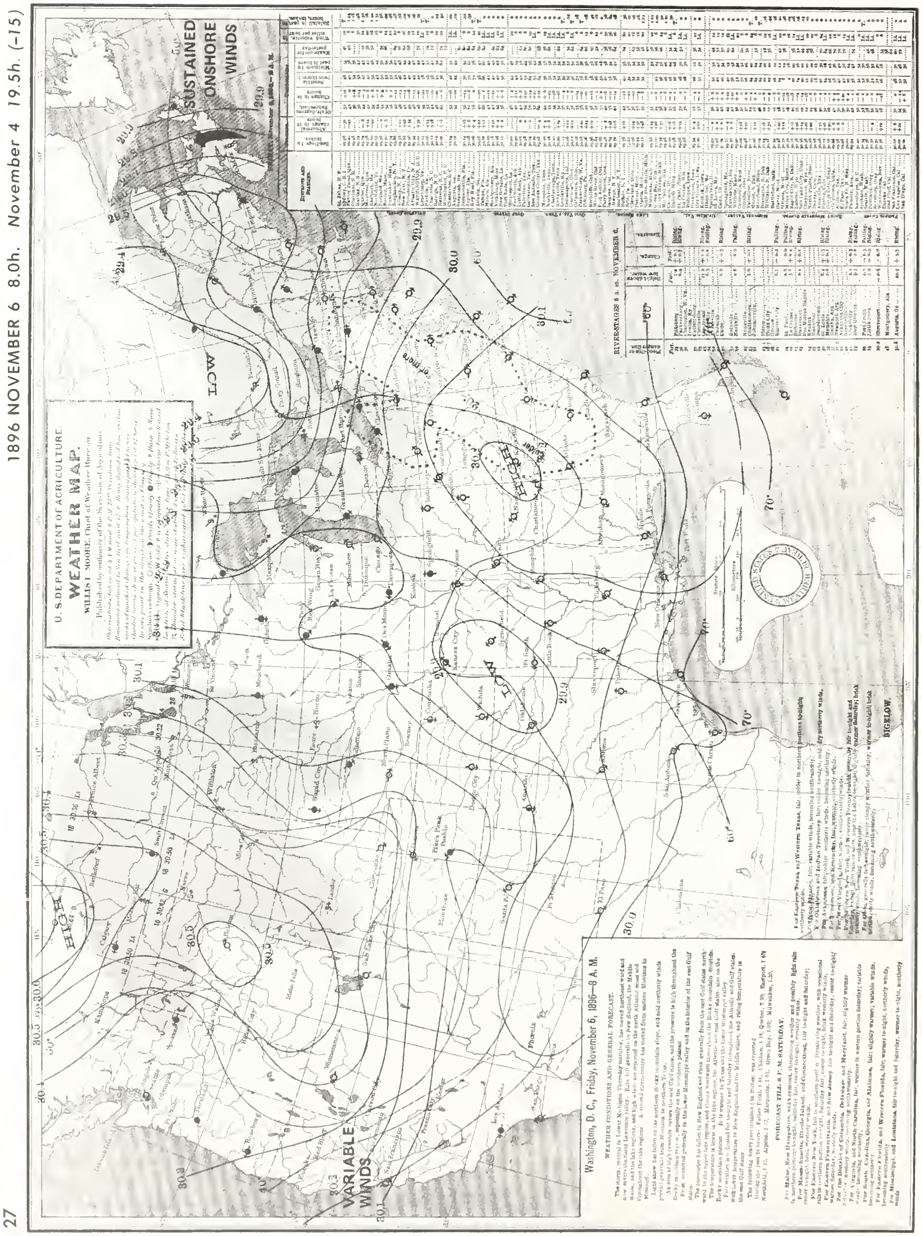
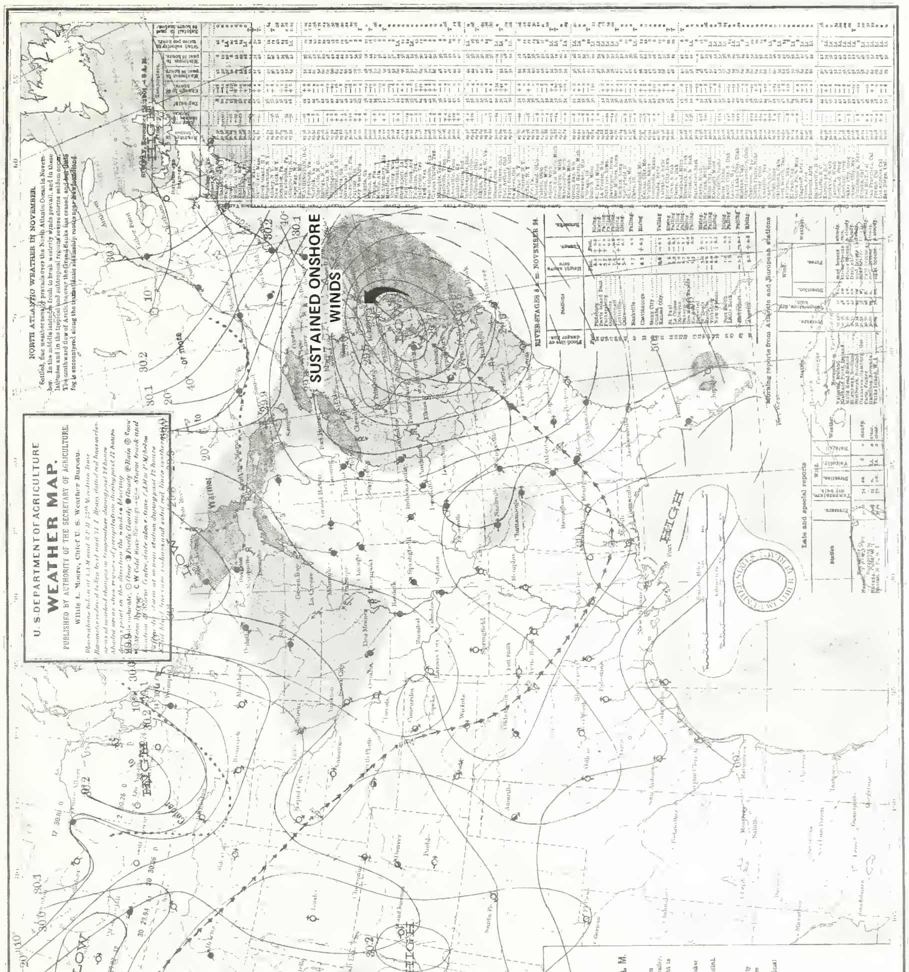

1896 NOVEMBER 6 8.0h. November 4 19.5h. (−15)
U.S. DEPARTMENT OF AGRICULTURE
WEATHER MAP
Washington, D. C., Friday, November 6, 1896—8 A. M.
SUSTAINED ONSHORE WINDS
VARIABLE WINDS
HIGH
LOW
27

FIGURE 51

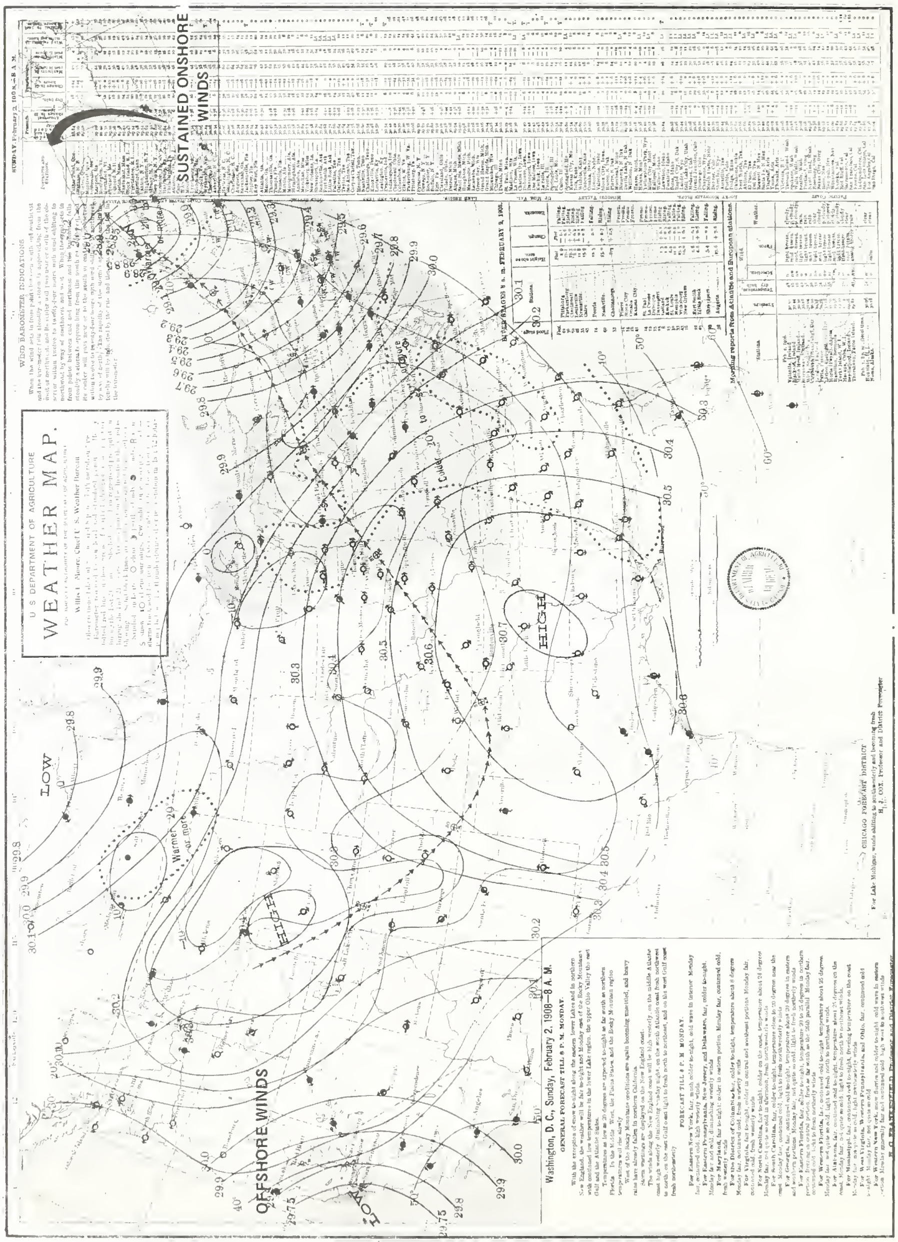
1901 NOVEMBER 24 8.0h. November 25 15.5h. (−9)



34

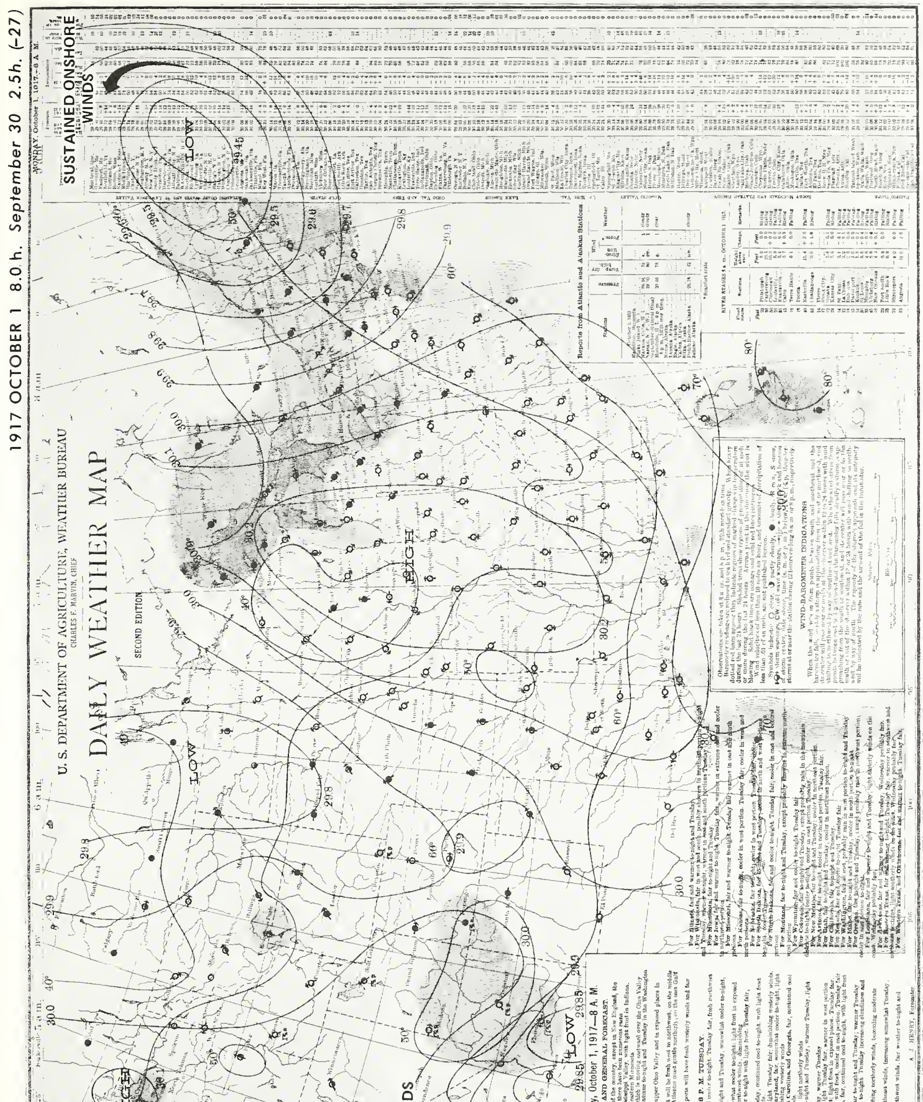
FIGURE 52

1908 FEBRUARY 2 8.0h. February 2 0.0h. (−8)



35

Figure 53



1917 OCTOBER 1 8.0 h. September 30 2.5h. (–27)
SUSTAINED ONSHORE WINDS
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
SECOND EDITION
HIGH
LOW
VARIABLE WINDS
Washington, D. C., Monday, October 1, 1917—8 A. M.
41

FIGURE 54

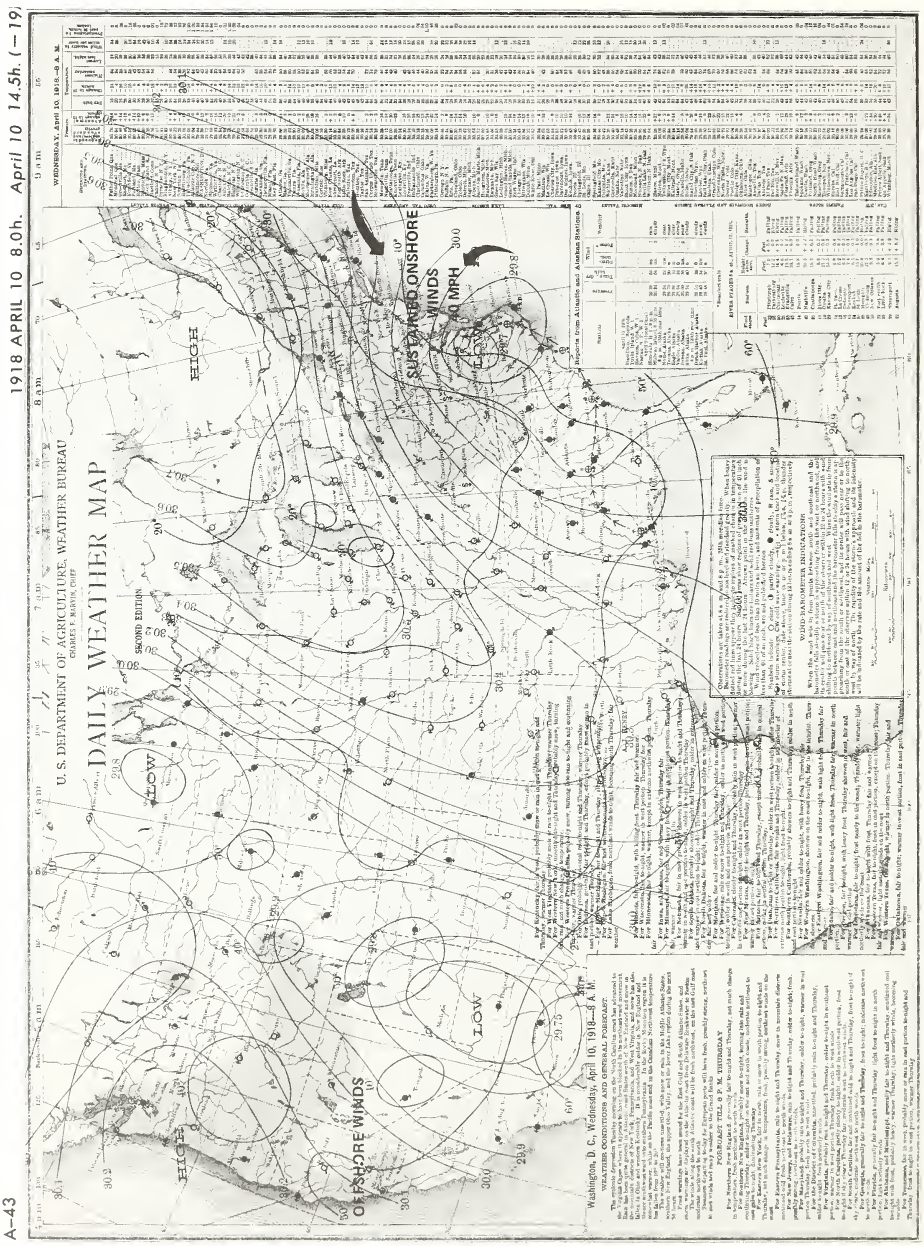

1918 APRIL 10 8.0h. April 10 14.5h. (−19)
A-43
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
SECOND EDITION
SUSTAINED ONSHORE WINDS
40 MPH
OFFSHORE WINDS
HIGH
LOW
Washington, D. C., Wednesday, April 10, 1918—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST
FORECAST TILL 8 P. M. THURSDAY
WIND-BAROMETER INDICATIONS
Reports from Atlantic and Alaskan Stations
WEDNESDAY, April 10, 1918—8 A. M.

FIGURE 55

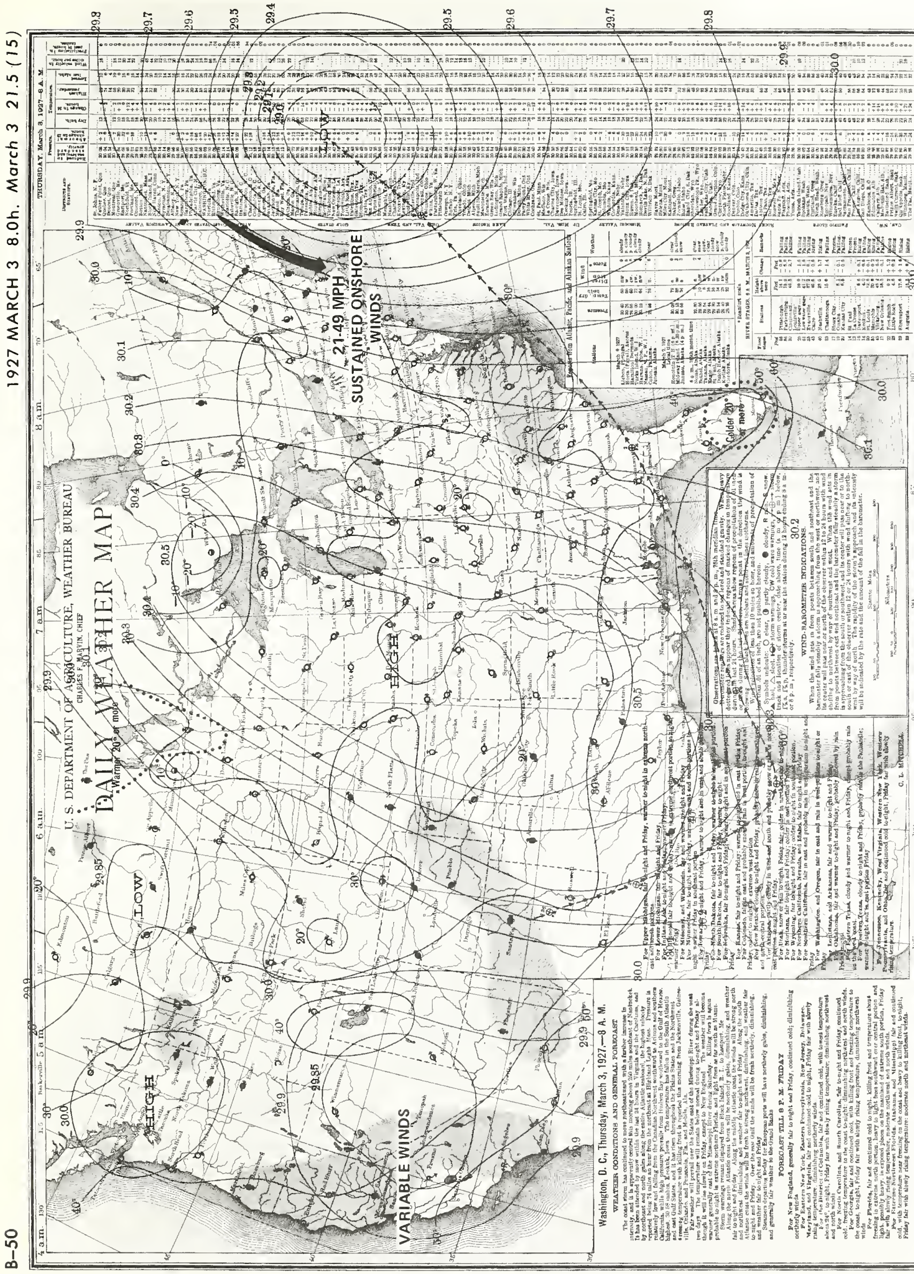

B–50
1927 MARCH 3 8.0h. March 3 21.5 (15)
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
Washington, D. C., Thursday, March 3, 1927.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST
FORECAST TILL 8 P. M. FRIDAY
WIND-BAROMETER INDICATIONS
21-49 MPH
SUSTAINED ONSHORE
WINDS
VARIABLE WINDS
Warmer 20° or more
Colder 20° or more
HIGH
LOW

FIGURE 56

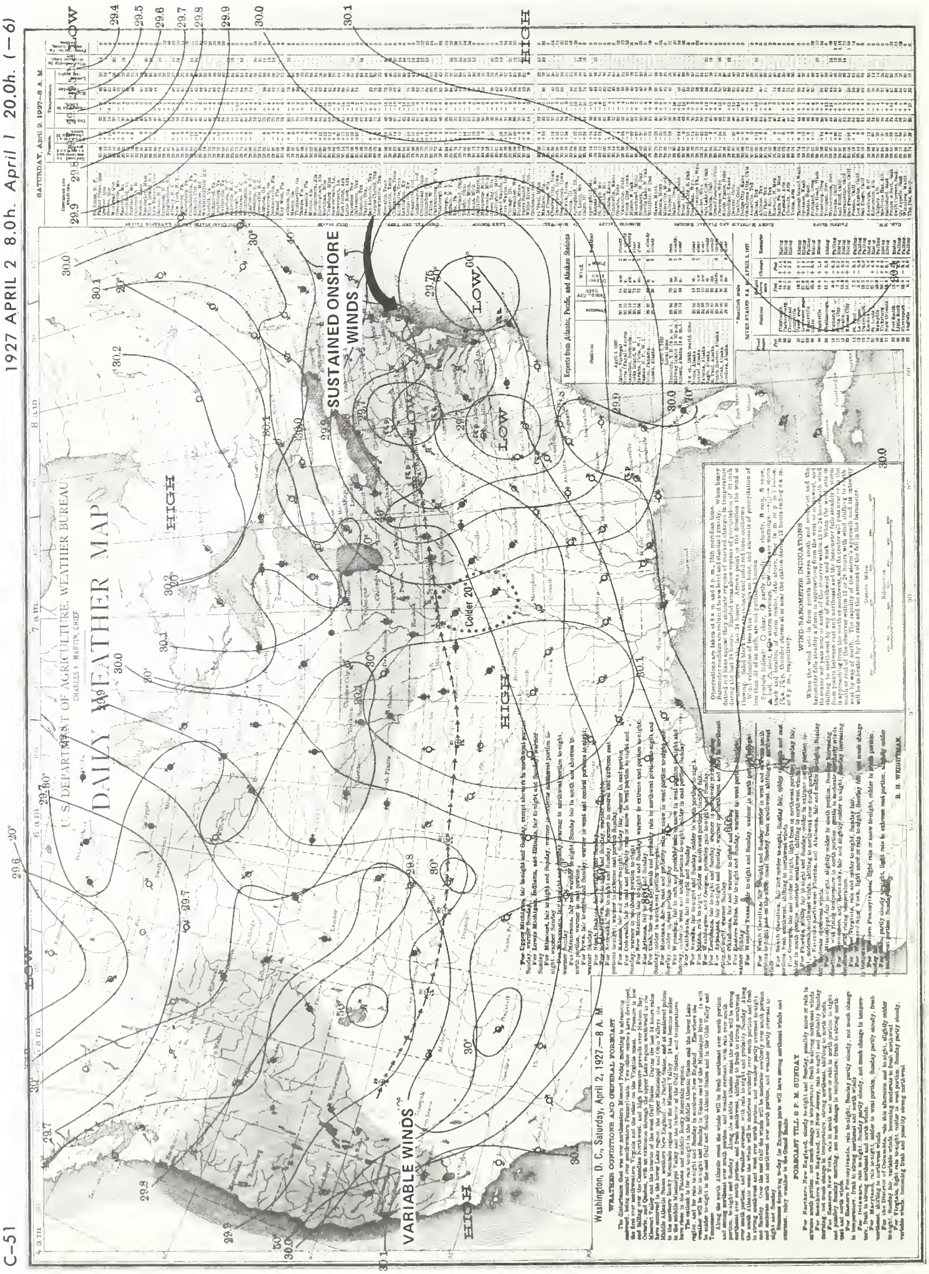

1927 APRIL 2 8.0h. April 1 20.0h. (−6)
C-51
U. S. DEPARTMENT OF AGRICULTURE. WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS
VARIABLE WINDS
HIGH
LOW
Washington, D. C., Saturday, April 2, 1927.—8 A. M.

FIGURE 57

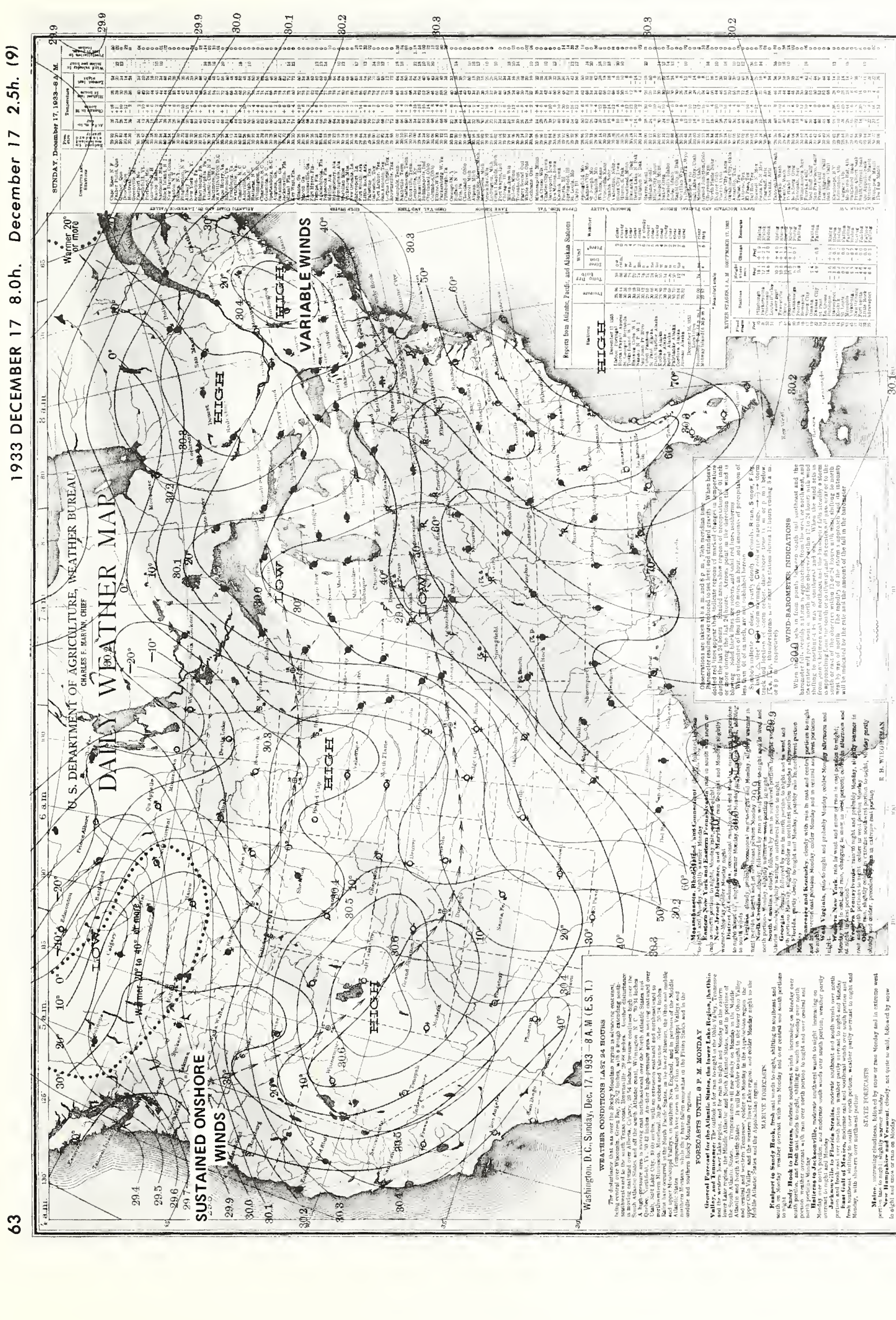
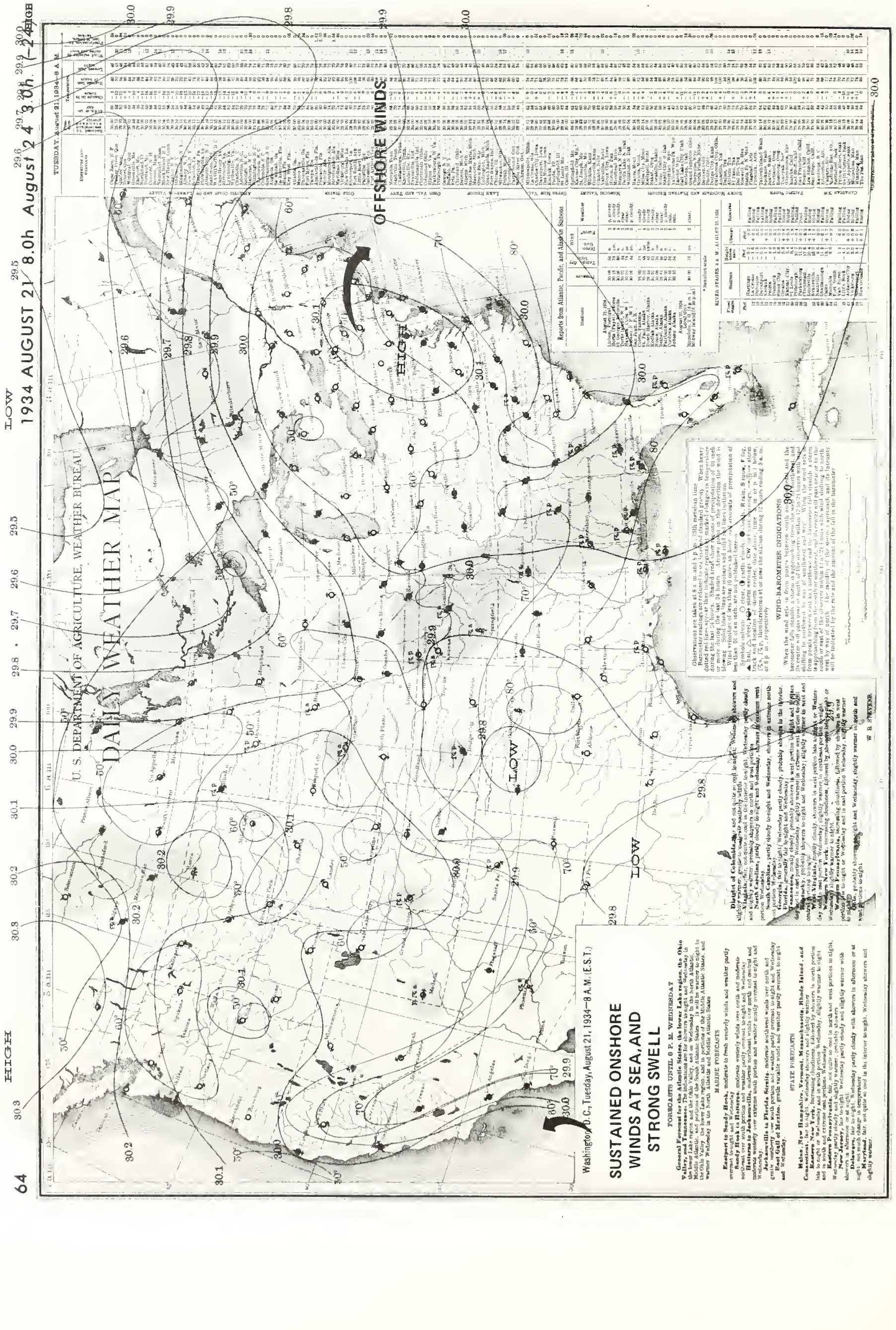

63
1933 DECEMBER 17 8.0h. December 17 2.5h. (9)
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
Washington, D. C., Sunday, Dec. 17, 1933—8 A. M. (E. S. T.)
WEATHER CONDITIONS LAST 24 HOURS
FORECASTS UNTIL 8 P. M. MONDAY
MARINE FORECASTS
STATE FORECASTS
SUSTAINED ONSHORE WINDS
VARIABLE WINDS
Warmer 20° or more
Warmer 20° to 40° or more
HIGH
LOW
WIND-BAROMETER INDICATIONS
RIVER STAGES
SUNDAY, December 17, 1933—8 A. M.

FIGURE 58



1934 AUGUST 21 8.0h August 24 3.0h (−24)
HIGH
LOW
64
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
Washington, D.C., Tuesday, August 21, 1934—8 A.M. (E.S.T.)
SUSTAINED ONSHORE WINDS AT SEA, AND STRONG SWELL
OFFSHORE WINDS

FIGURE 59

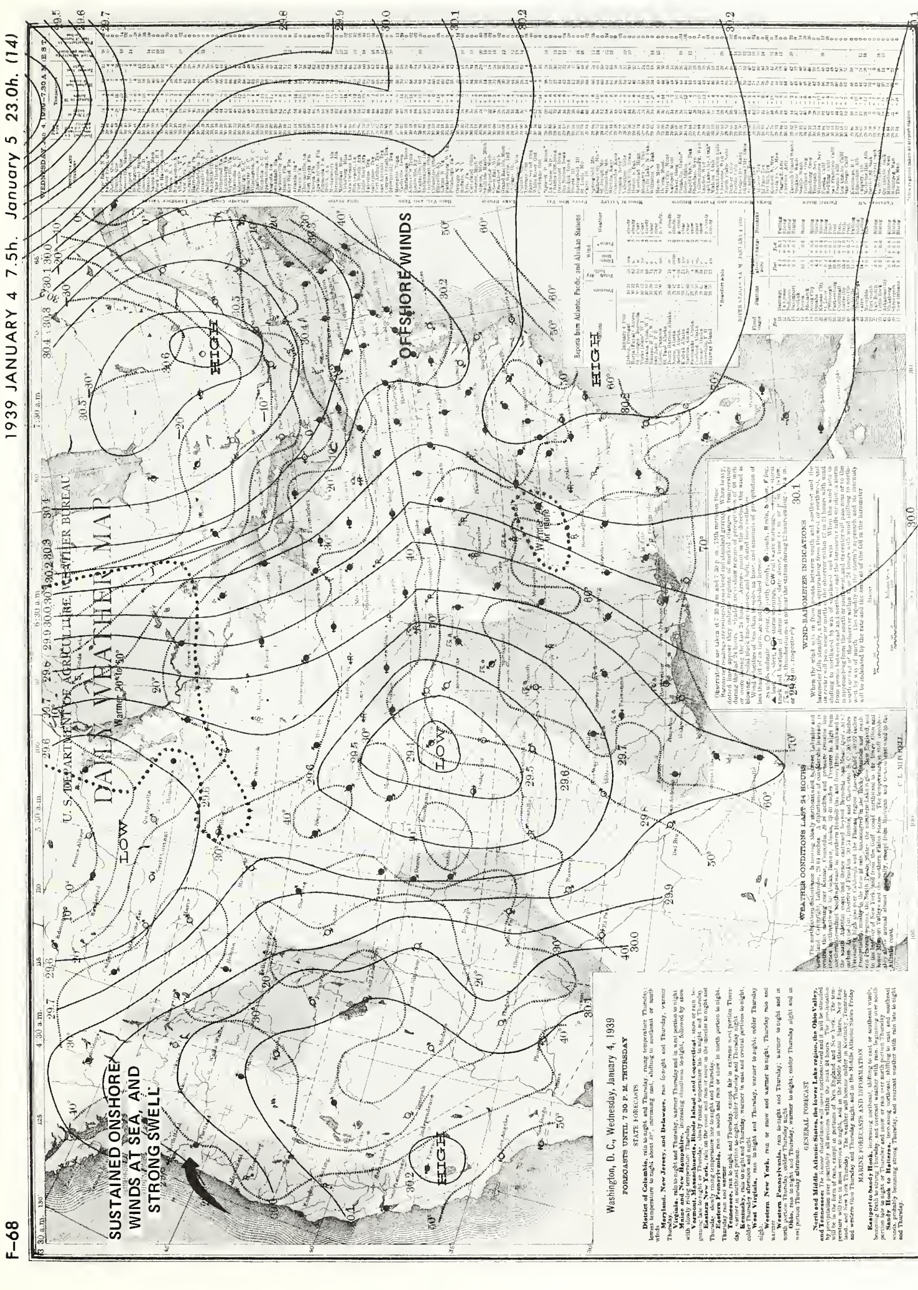

1939 JANUARY 4 7.5h. January 5 23.0h. (14)
F–68
U. S. DEPARTMENT OF AGRICULTURE WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS AT SEA, AND STRONG SWELL
OFFSHORE WINDS
HIGH
LOW
HIGH
LOW
HIGH
Washington, D. C., Wednesday, January 4, 1939
FORECASTS UNTIL 7 30 P. M. THURSDAY
WIND-BAROMETER INDICATIONS
WEATHER CONDITIONS LAST 24 HOURS

FIGURE 60

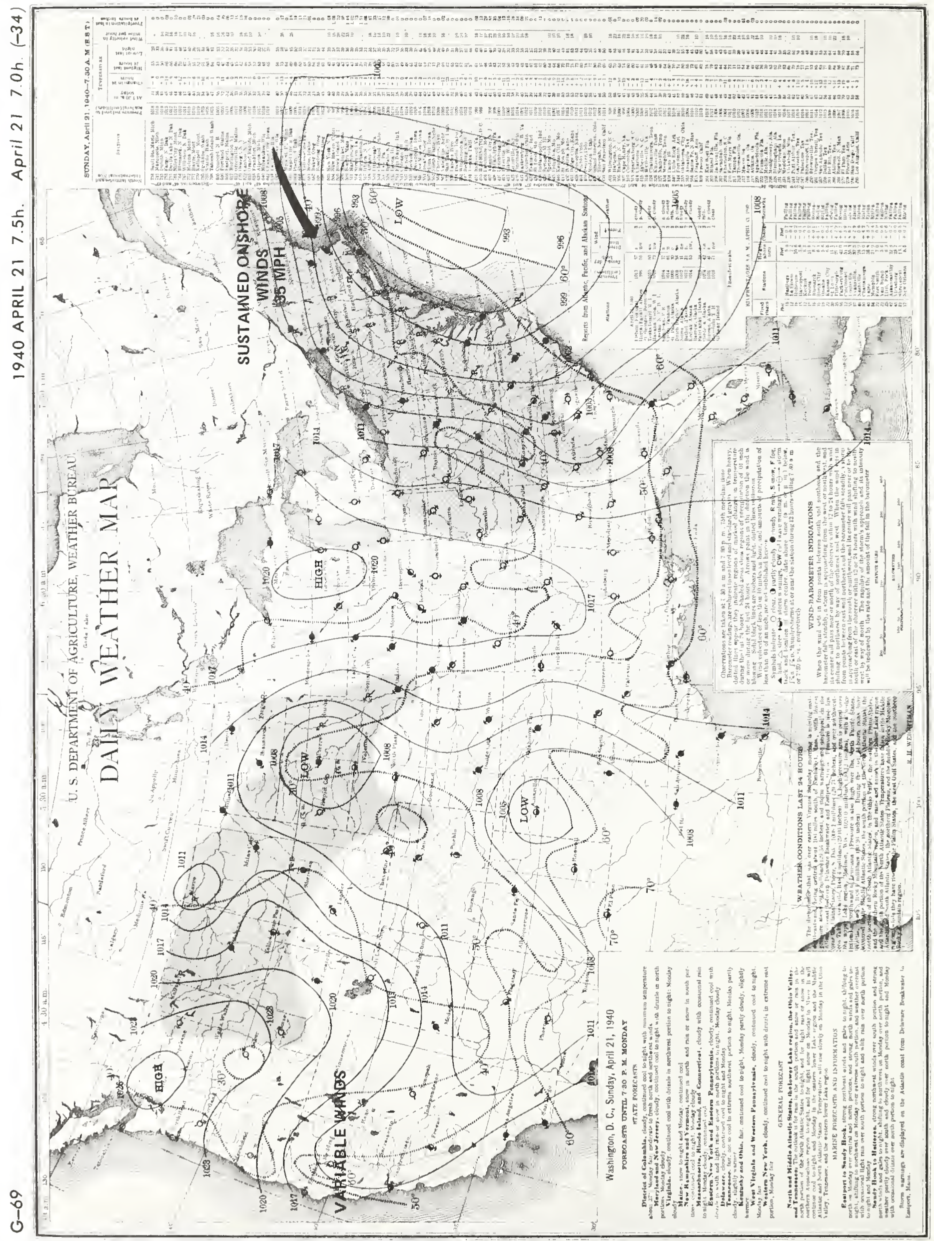

1940 APRIL 21 7.5h. April 21 7.0h. (–34)
G–69
U.S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS 35 MPH
VARIABLE WINDS
HIGH
LOW
Washington, D.C., Sunday, April 21, 1940
WEATHER CONDITIONS LAST 24 HOURS
WIND-BAROMETER INDICATIONS

FIGURE 61

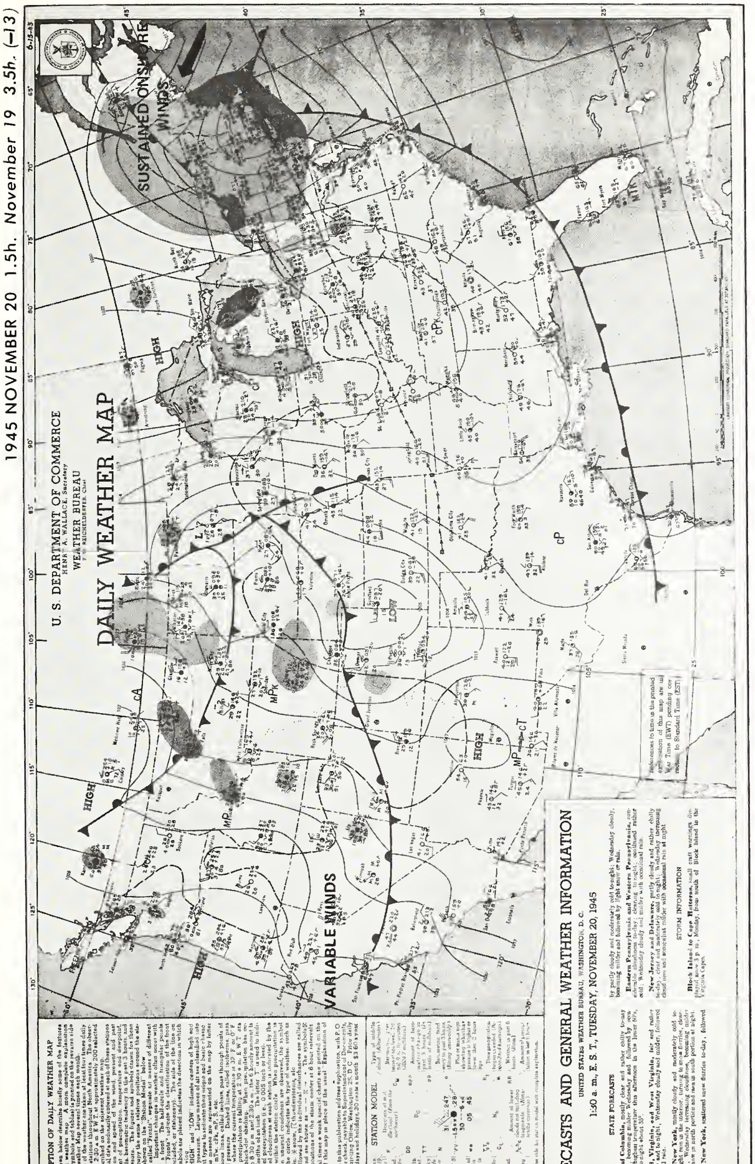
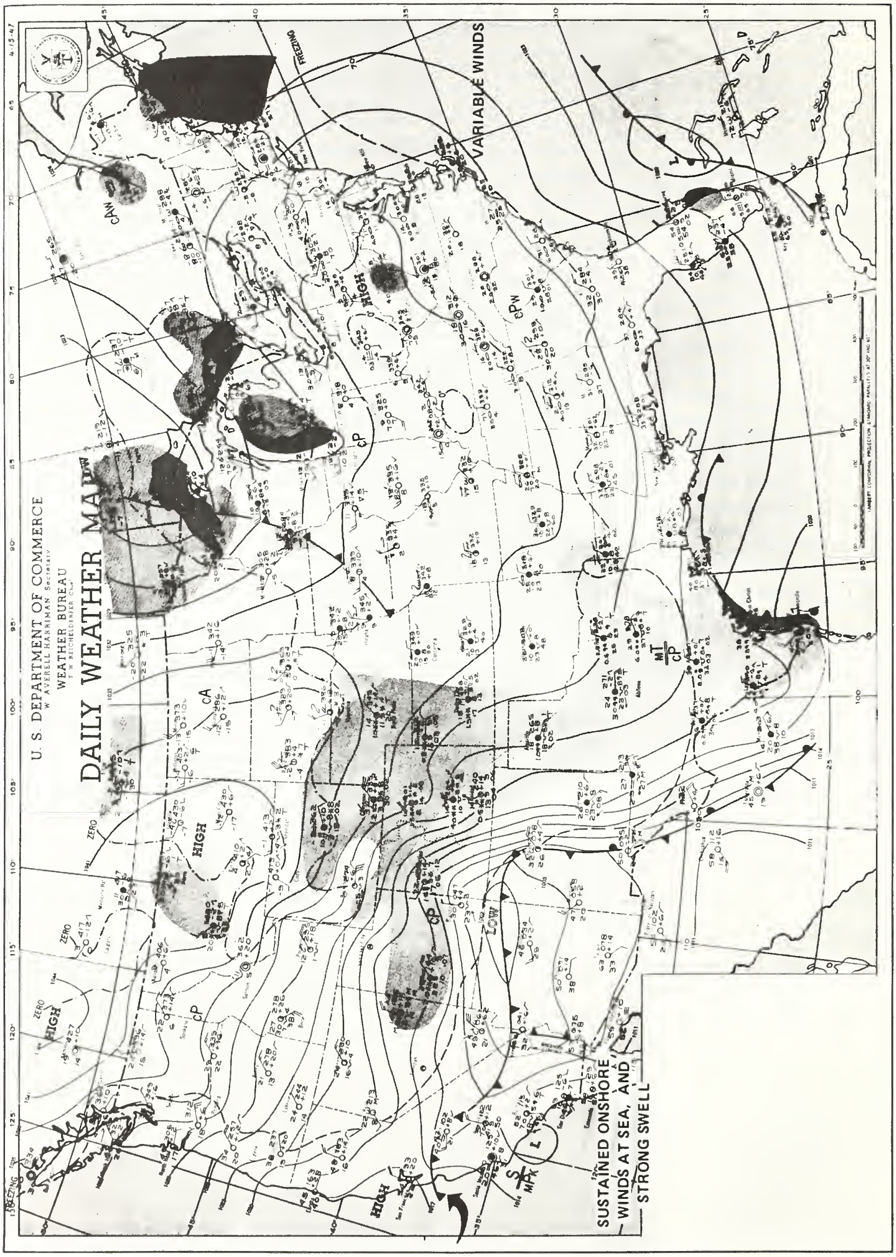

1945 NOVEMBER 20 1.5h. November 19 3.5h. (−13)
H–72
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS
VARIABLE WINDS
HIGH
LOW
FORECASTS AND GENERAL WEATHER INFORMATION
DESCRIPTION OF DAILY WEATHER MAP
STATION MODEL
STATE FORECASTS
STORM INFORMATION

Figure 62

1948 JANUARY 26 1.5h. January 26 4.0h. (4)



74

FIGURE 63

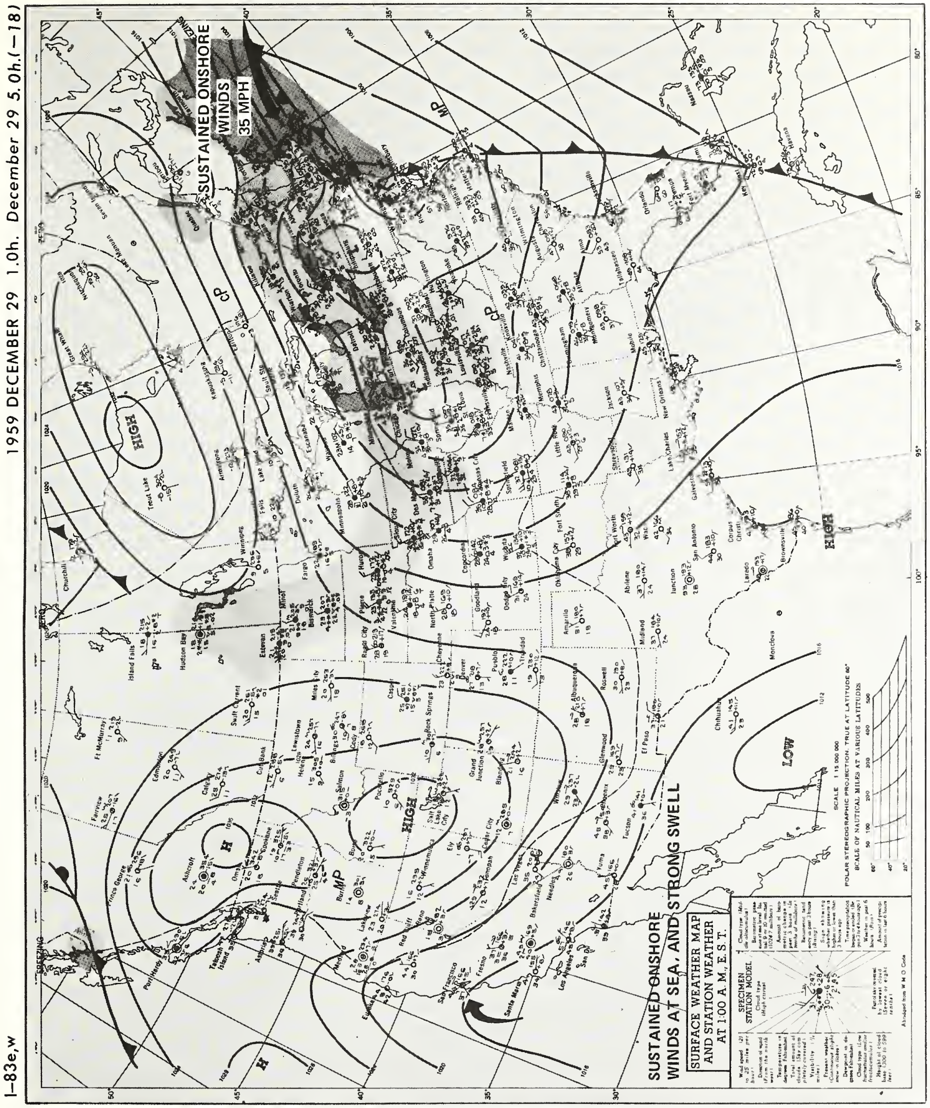

1959 DECEMBER 29 1.0h. December 29 5.0h.(−18)
1–83e,w
SUSTAINED ONSHORE WINDS 35 MPH
SUSTAINED ONSHORE WINDS AT SEA, AND STRONG SWELL
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
LOW
cP
mP

FIGURE 64

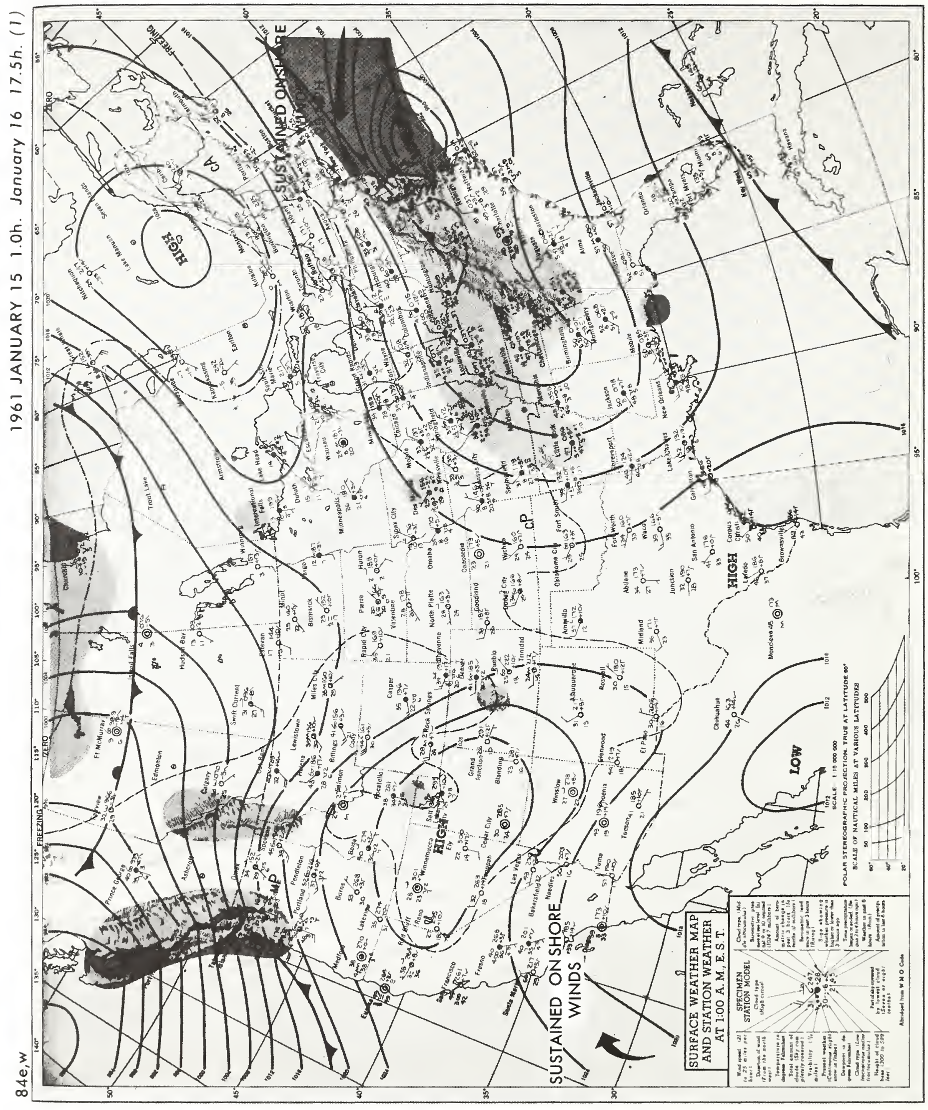

1961 JANUARY 15 1.0h. January 16 17.5h. (1)
84e,w
SUSTAINED ON SHORE WINDS
SUSTAINED ON SHORE WINDS
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.
HIGH
HIGH
HIGH
LOW

FIGURE 65

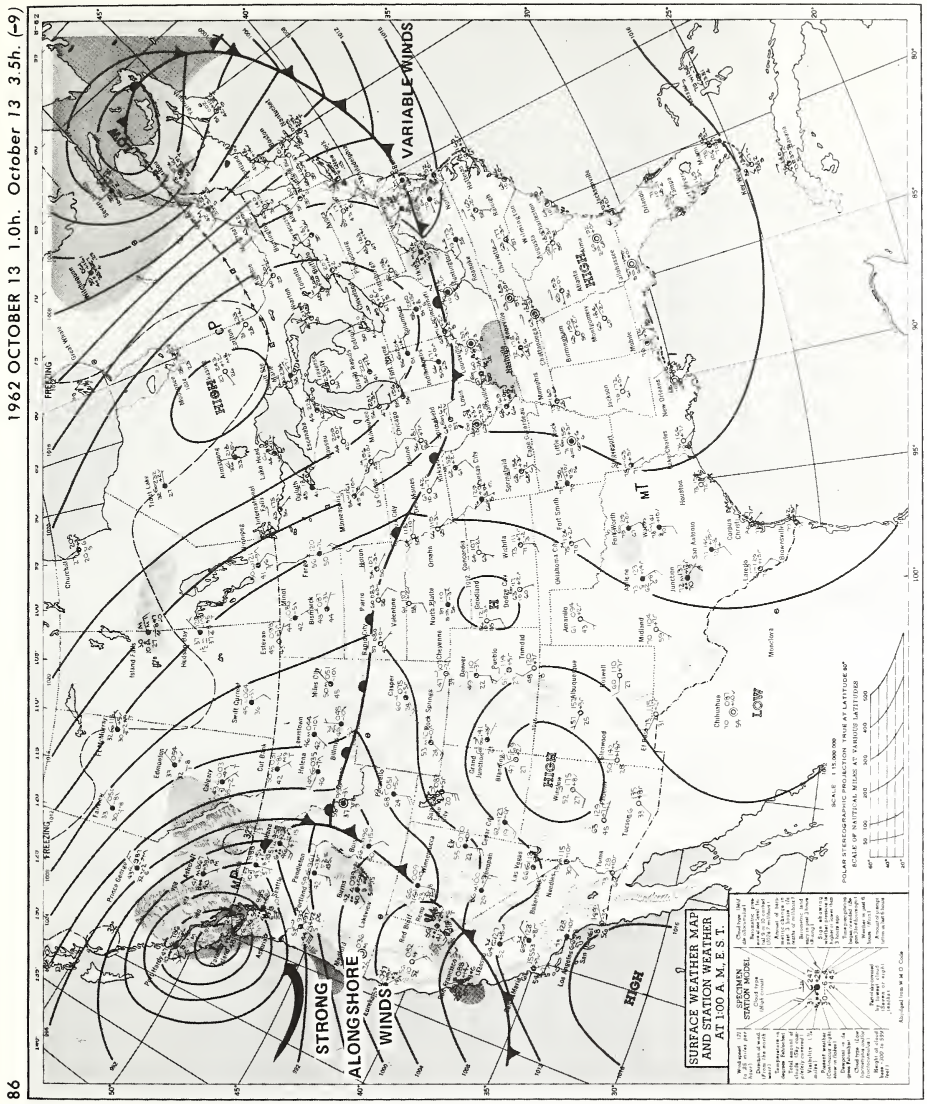

1962 OCTOBER 13 1.0h. October 13 3.5h. (−9)
86
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A. M., E. S. T.
STRONG ALONGSHORE WINDS
VARIABLE WINDS
HIGH
LOW
FREEZING

Figure 66

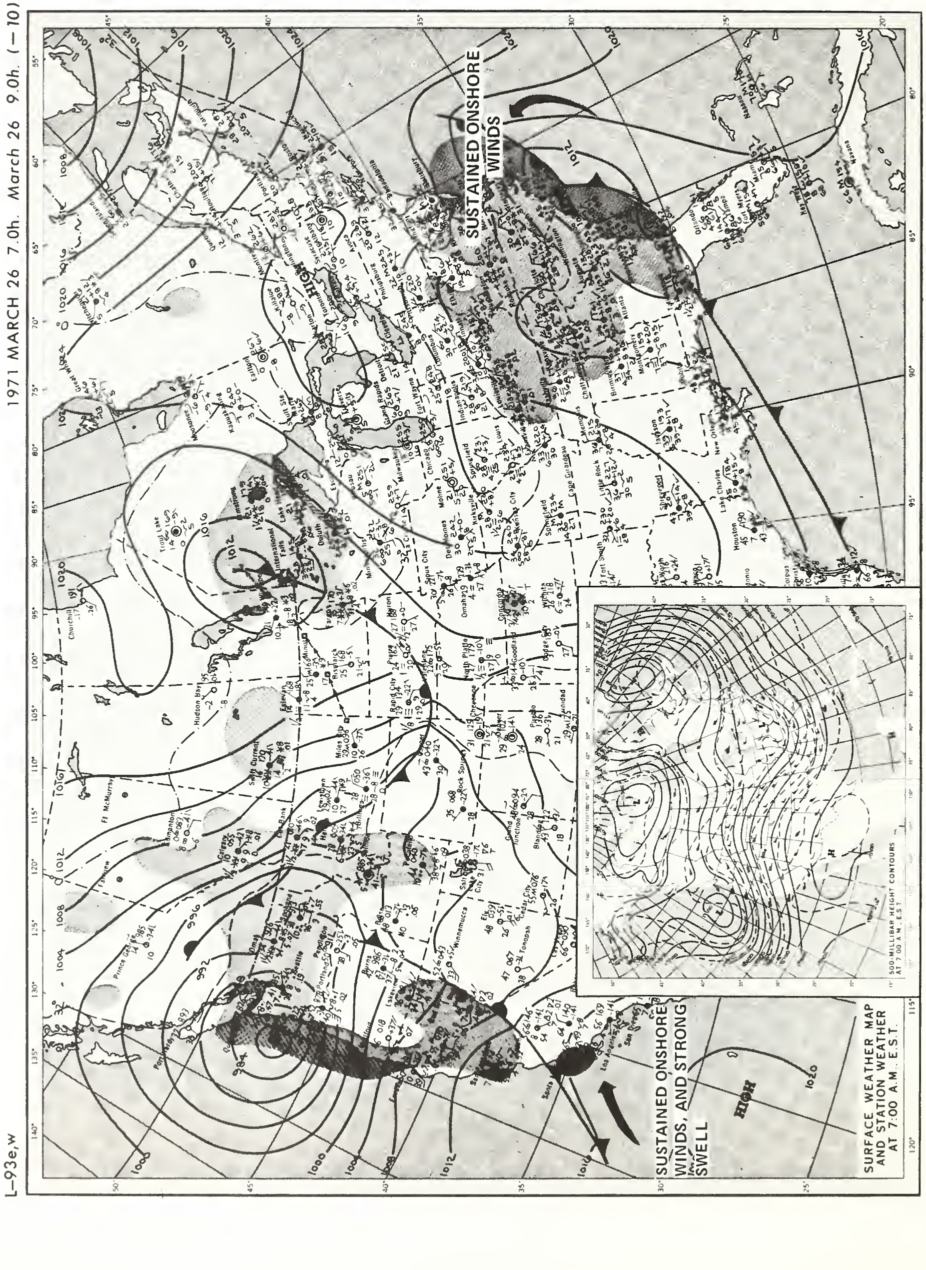

1971 MARCH 26 7.0h. March 26 9.0h. (−10)
L–93e,w
SUSTAINED ONSHORE WINDS
SUSTAINED ONSHORE WINDS, AND STRONG SWELL
HIGH
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.

FIGURE 67

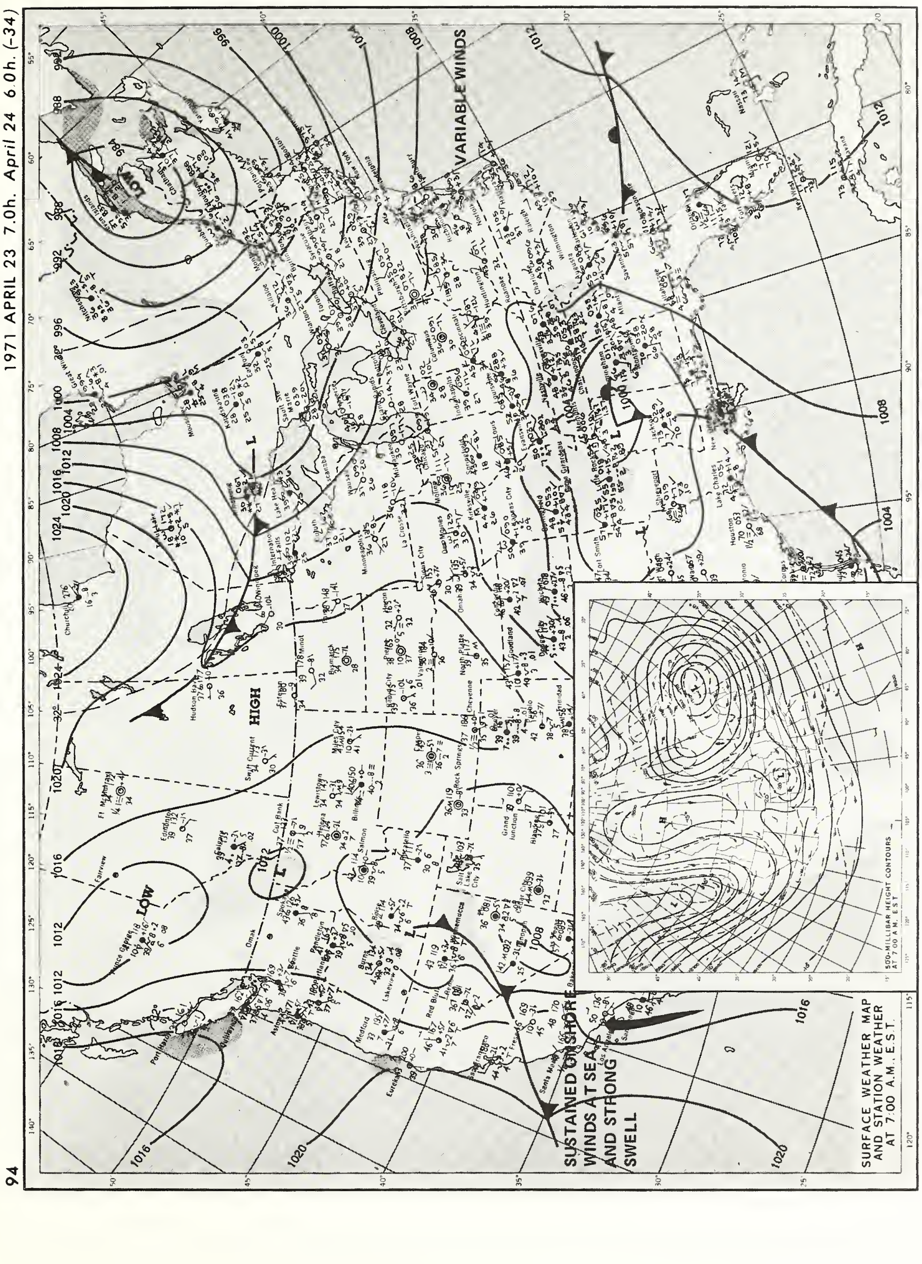

1971 APRIL 23 7.0h. April 24 6.0h. (-34)
94
VARIABLE WINDS
SUSTAINED ONSHORE WINDS AT SEA AND STRONG SWELL
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M., E.S.T.
500-MILLIBAR HEIGHT CONTOURS AT 7:00 A.M. E.S.T.

FIGURE 68

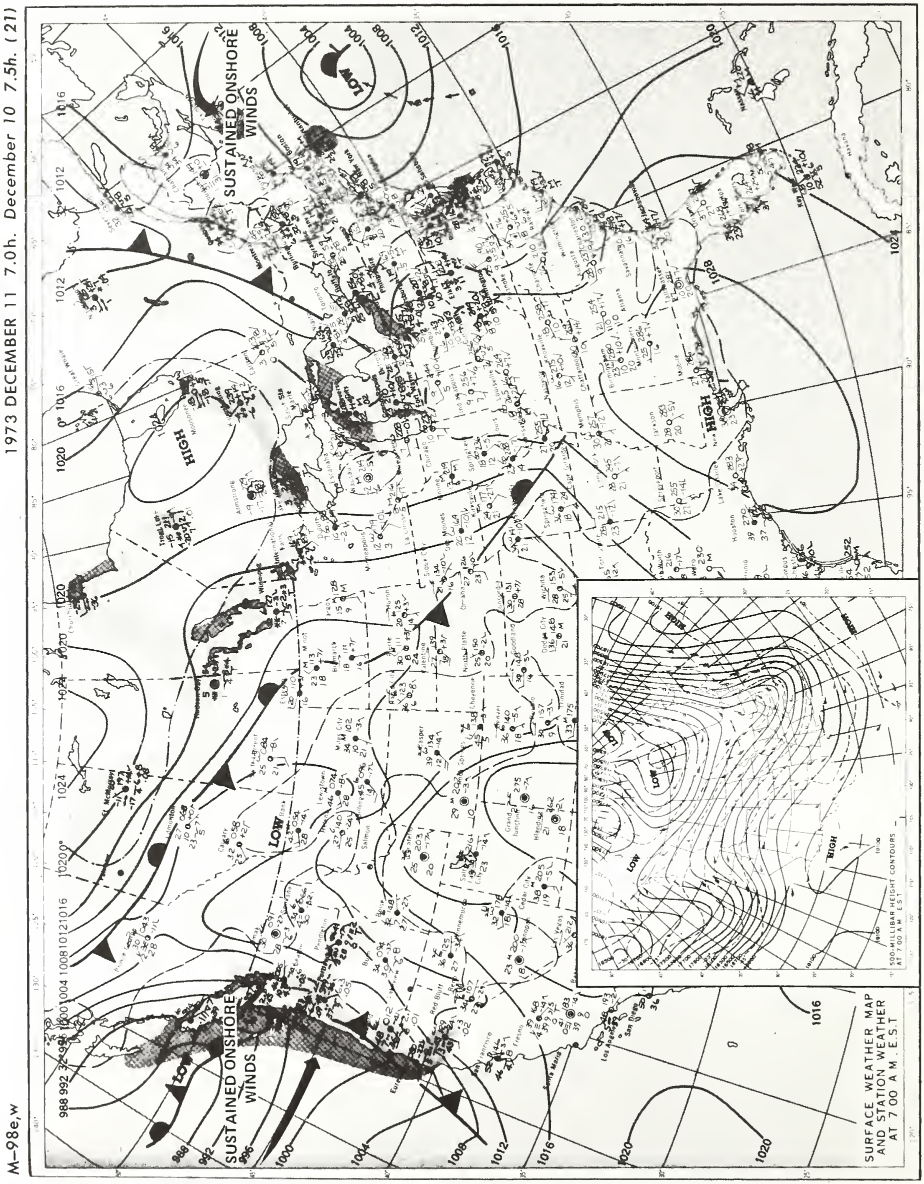

1973 DECEMBER 11 7.0h. December 10 7.5h. (21)
M–98e,w
SUSTAINED ONSHORE WINDS
SUSTAINED ONSHORE WINDS
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 7 00 A M. E.S.T.
500-MILLIBAR HEIGHT CONTOURS AT 7 00 A M E S T

FIGURE 69

TABLE 27.—*Surface Synoptic Weather Maps for Twenty Representative Cases of Nonflooding Conditions Associated With Perigean Spring Tides Which Were Accompanied by Light and Variable Winds and High Atmospheric Pressure*

Serial No.	Weather map date and mean perigee-syzygy date l. s. t.	Perigee —syzygy (in hours)	Remarks
151	1893 December 23 20.0h December 22 23.0h	(− 2)	Near-maximum parallax and declination, occurring at the winter solstice and near perihelion.
152	1899 January 12 8.0h January 11 19.5h	(+3)	Large parallax; close to perihelion.
153	1912 January 5 8.0h January 4 8.5h	(+6.5 *min.*)	Near maximum parallax; occurring at perihelion; very close separation-interval.
154	1922 September 22 8.0h September 21 0.5h	(+1)	Total solar eclipse; autumnal equinox; and Moon very nearly on Equator.
155	1923 November 9 8.0h November 8 10.0h	(−27 *min.*)	Large parallax; very close separation-interval.
156	1928 November 28 8.0h November 27 6.5h	(+5)	Large parallax and positive declination.
157	1930 January 15 8.0h January 14 18.0h	(+2)	Near maximum parallax and high positive declination, occurring near perihelion.
158	1935 September 13 8.0h September 12 14.0h	(−2)	Very large parallax; Moon very nearly on Equator.
159	1940 October 2 7.5h October 1 9.5h	(+3)	Total solar eclipse; Moon near Equator.
160	1944 October 2 1.5h October 1 17.5h	(−11)	Moon very nearly on Equator.
161	1950 May 3 1.5h May 2 1.0h	(+2)	Large parallax; close separation-interval.
162	1950 December 9 1.5h December 9 1.0h	(−8)	Large parallax; very high negative declination (ascending node at the vernal equinox).
163	1951 June 20 1.5h June 19 8.0h	(+1)	Summer solstice and maximum declination of Sun (+) and Moon (−); close separation-interval.
164	1953 September 24 1.5h September 22 23.0h	(−15 *min.*)	Autumnal equinox, large parallax, and Moon near Equator; very close separation-interval.
165	1954 November 10 1.5h November 10 9.0h	(−1)	Large parallax; close separation-interval.
166	1966 September 14 1.0h September 14 13.0h	(−2)	Large parallax.
167	1967 March 27 1.0h March 26 0.5h	(+5)	Moon near vernal equinox and on Equator.
168	1968 December 19 7.0h December 19 10.0h	(−6)	Large parallax and high negative declination.
169	1972 December 20 7.0h December 19 18.5h	(−21)	Near winter solstice; full moon at high positive declination, nearly coplanar with negative declination of Sun.
170	1974 February 6 7.0h February 6 6.0h	(−24)	Declination of full moon (+15°19′) nearly coplanar with declination of Sun (−15°39′).

(Commonwealth Pier) on 1931 March 6 at 1243^h (e.s.t.) −55 hours after the mean epoch of perigee-syzygy on 1931 March 4 at 0530^h (e.s.t.)—was 11.0 ft. The maximum tidal *range* on March 6 was 13.0 ft. These values compare respectively with 10.3 ft for mean high water springs and 10.9 ft (or 11.0 ft in the 1977 tide table) for the spring range of the tide at Boston.

It will be demonstrated in chapter 8 that the likelihood of an increased amount of tidal flooding is associated, not alone with the predicted amplitude and range of perigean spring tides, but with their accelerated rate of growth in reaching this maximum. Thus figure 96, which depicts the predicted rate of tide rise (in ft/min$\times$0.0001) at Willetts Point, N.Y., during successive lunations bracketing 1931 March 4–5, is far more meaningful in indicating the potential for the tidal flooding which actually occurred. The use of such rate-of-growth tide curves of perigean spring tides and the determination of their respective "windows for potential flooding" will be discussed further in part II, chapter 8.

The peaking of those portions of the tidal curve containing perigean spring tides at a level considerably above the baseline representing the average rate of tide growth throughout the entire year at this location is clearly evi-

202-509 O - 78 - 25

151

1893 DECEMBER 23 20.0h. December 22 23.0h. (−2)

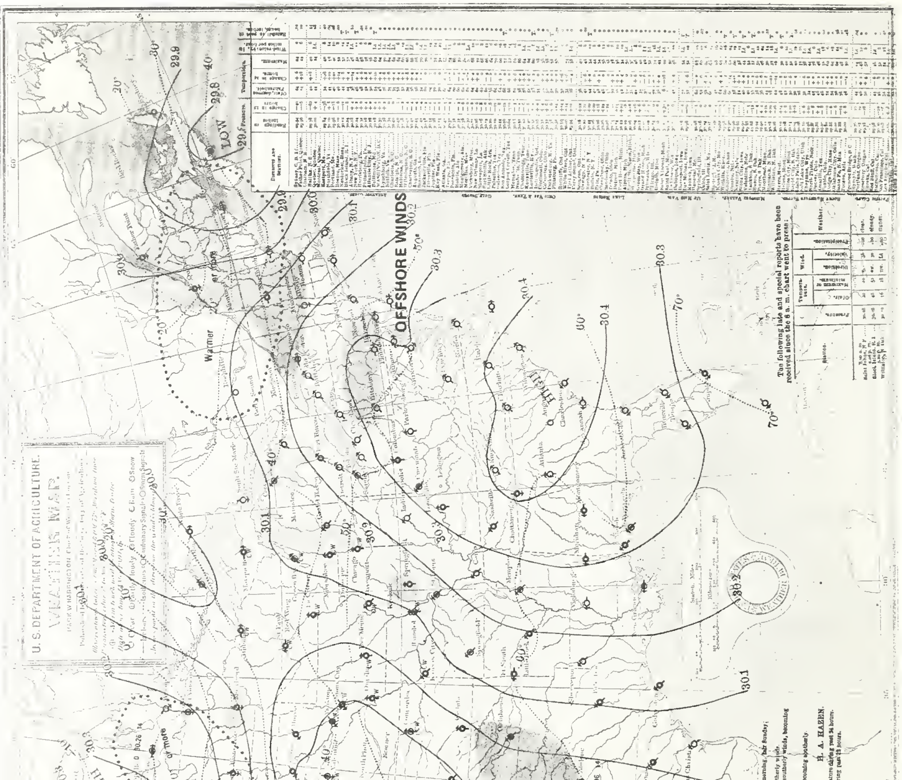
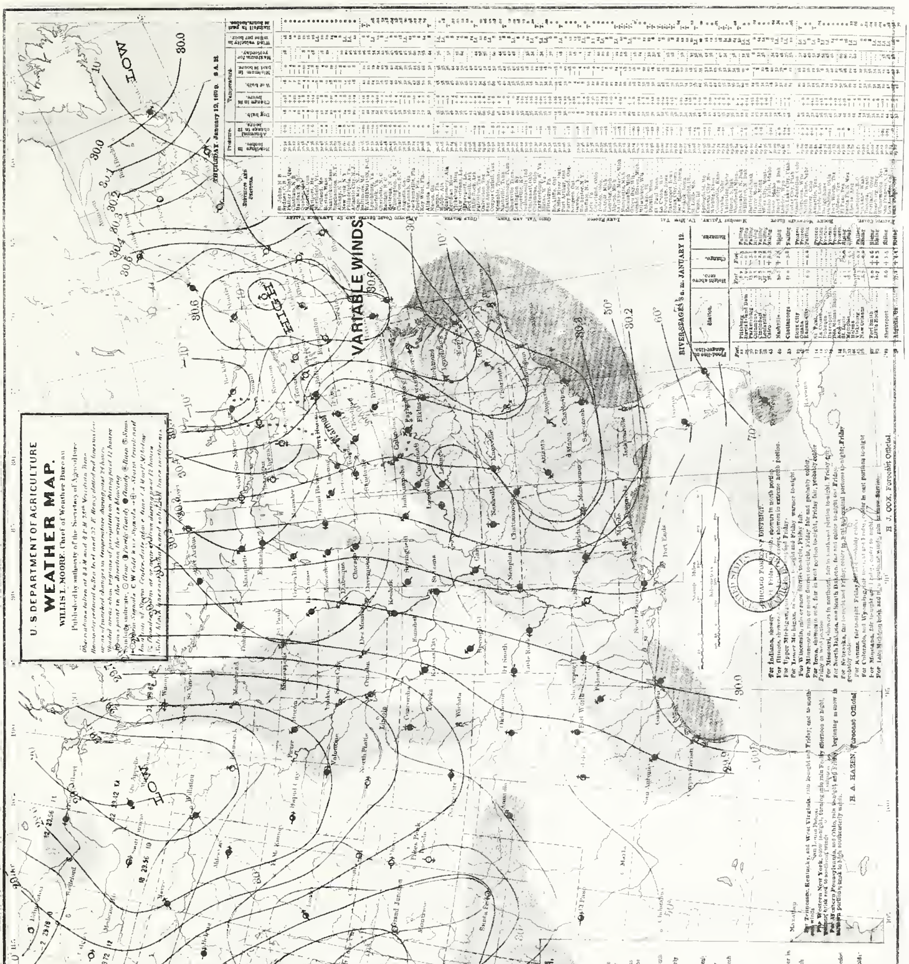


FIGURE 70

1899 JANUARY 12 8.0h. January 11 19.5h. (3)



152

FIGURE 71

153 1912 JANUARY 5 8.0h. January 4 8.5h. (0)

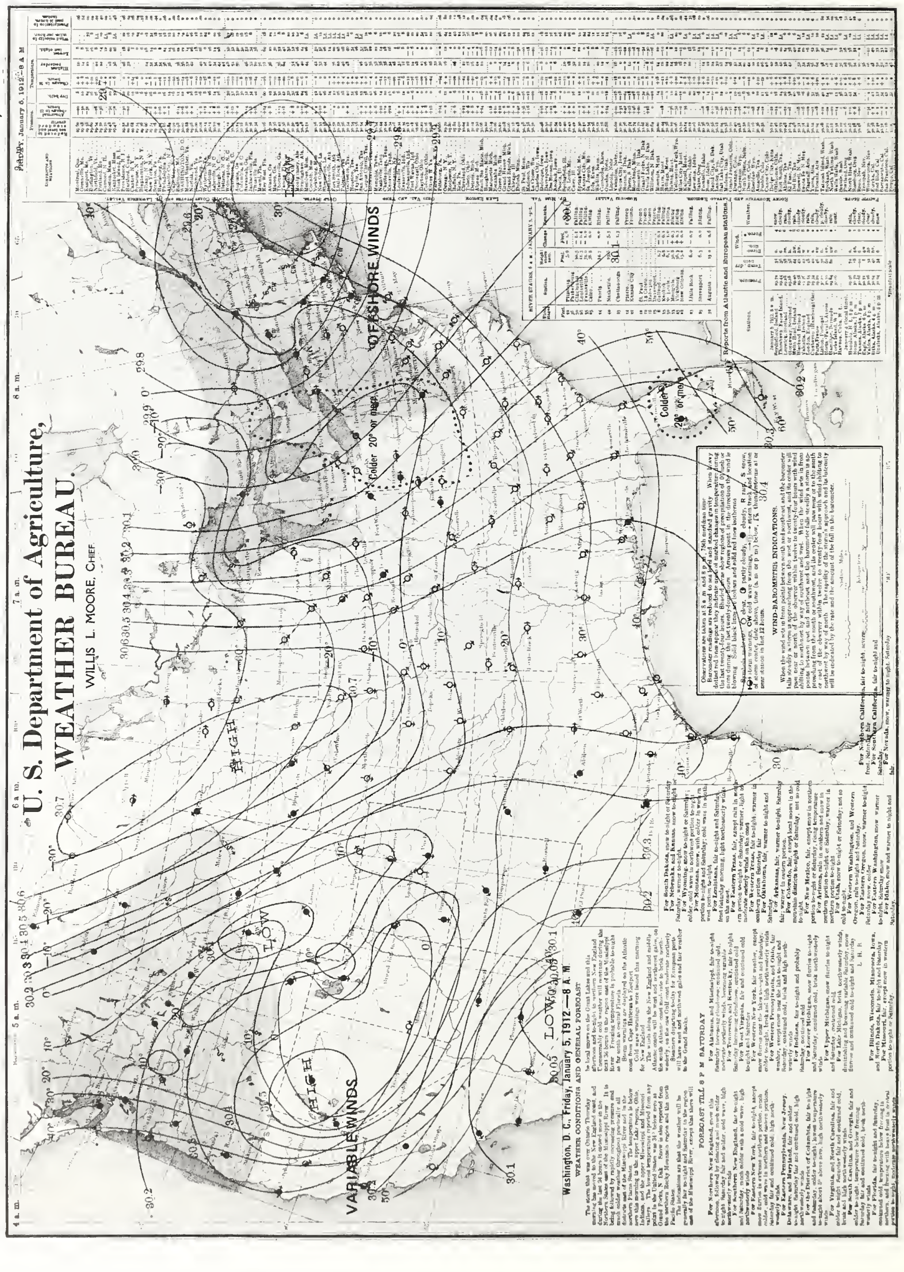


FIGURE 72

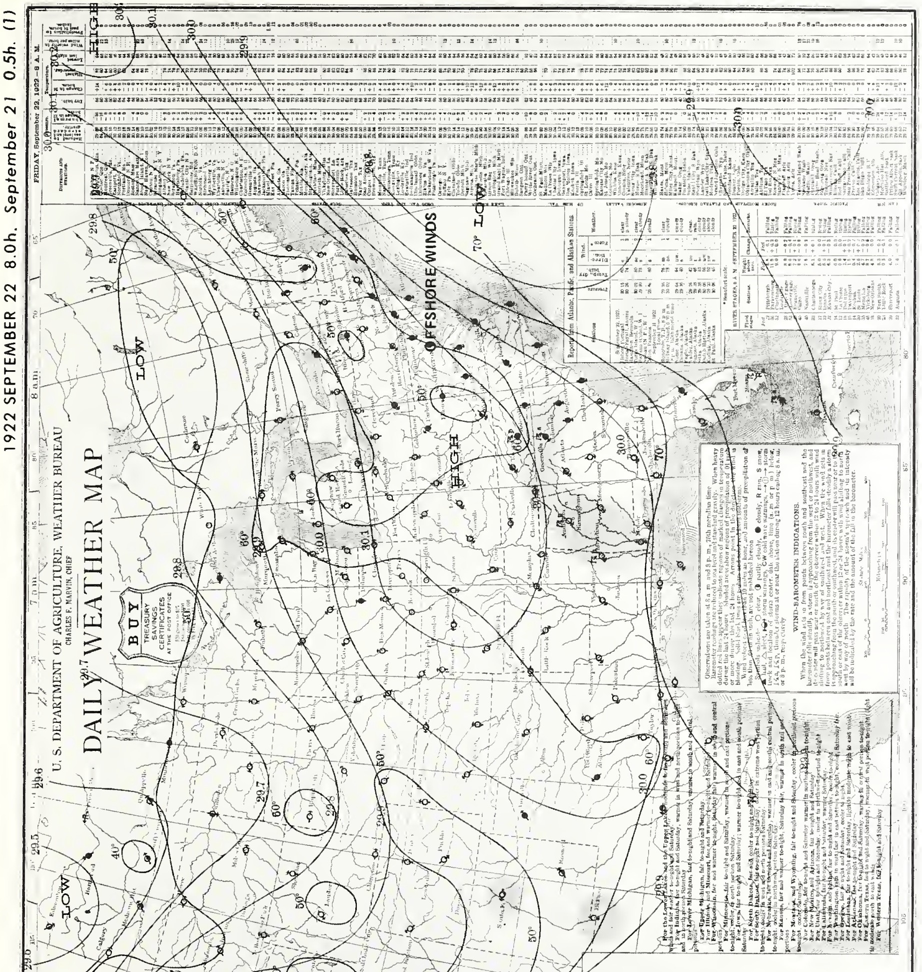

1922 SEPTEMBER 22 8.0h. September 21 0.5h. (1)
154
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
BUY TREASURY SAVINGS CERTIFICATES AT THE POST OFFICE
Washington, D. C., Friday, September 22, 1922.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
E. H. BOWIE.
VARIABLE WINDS
OFFSHORE WINDS
HIGH
LOW
WIND-BAROMETER INDICATIONS.
Reports from Atlantic, Pacific, and Alaskan Stations.
RIVER STAGES, 8 A. M., SEPTEMBER 22, 1922.

FIGURE 73

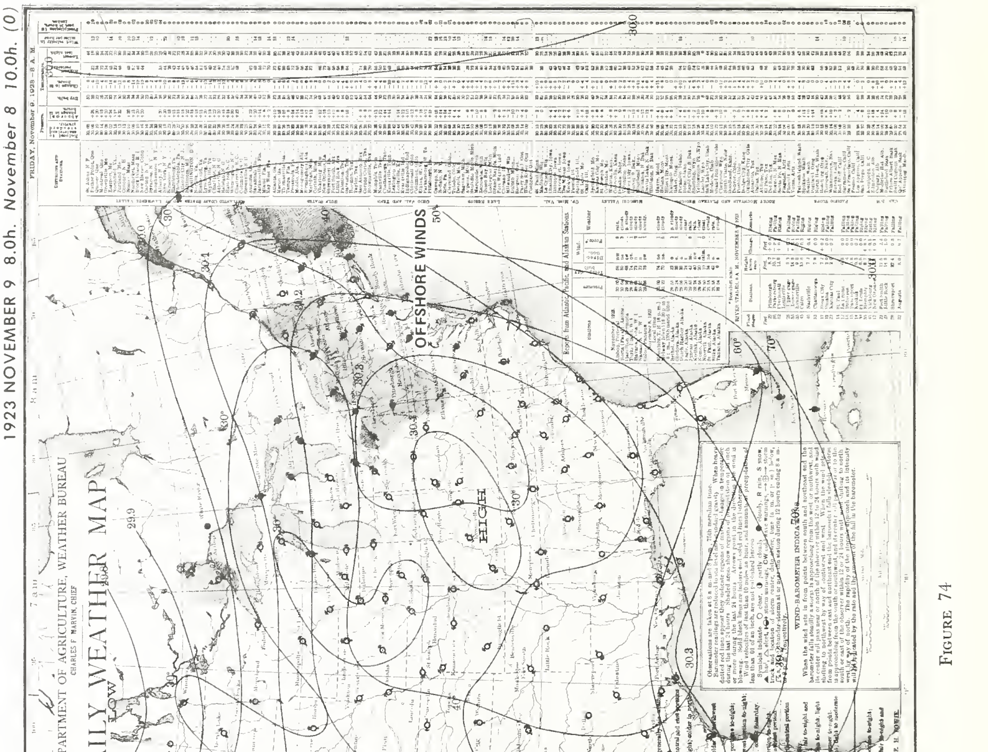

1923 NOVEMBER 9 8.0h. November 8 10.0h. (0)
155
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
VARIABLE WINDS
OFFSHORE WINDS
HIGH
HIGH
LOW
LOW
Washington, D. C., Friday, November 9, 1923.—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST.
FORECAST TILL 8 P. M. SATURDAY.
WIND-BAROMETER INDICATIONS.

FIGURE 74

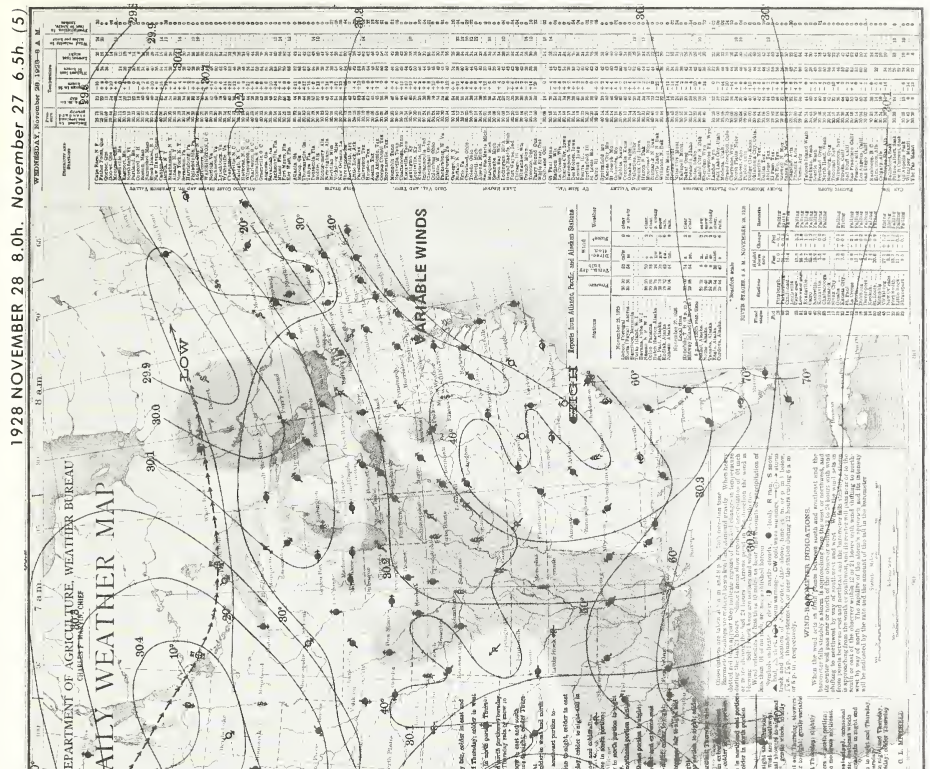

1928 NOVEMBER 28 8.0h. November 27 6.5h. (5)
156
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
HIGH
LOW
VARIABLE WINDS
Washington, D. C., Wednesday, November 28, 1928—8 A. M.

FIGURE 75

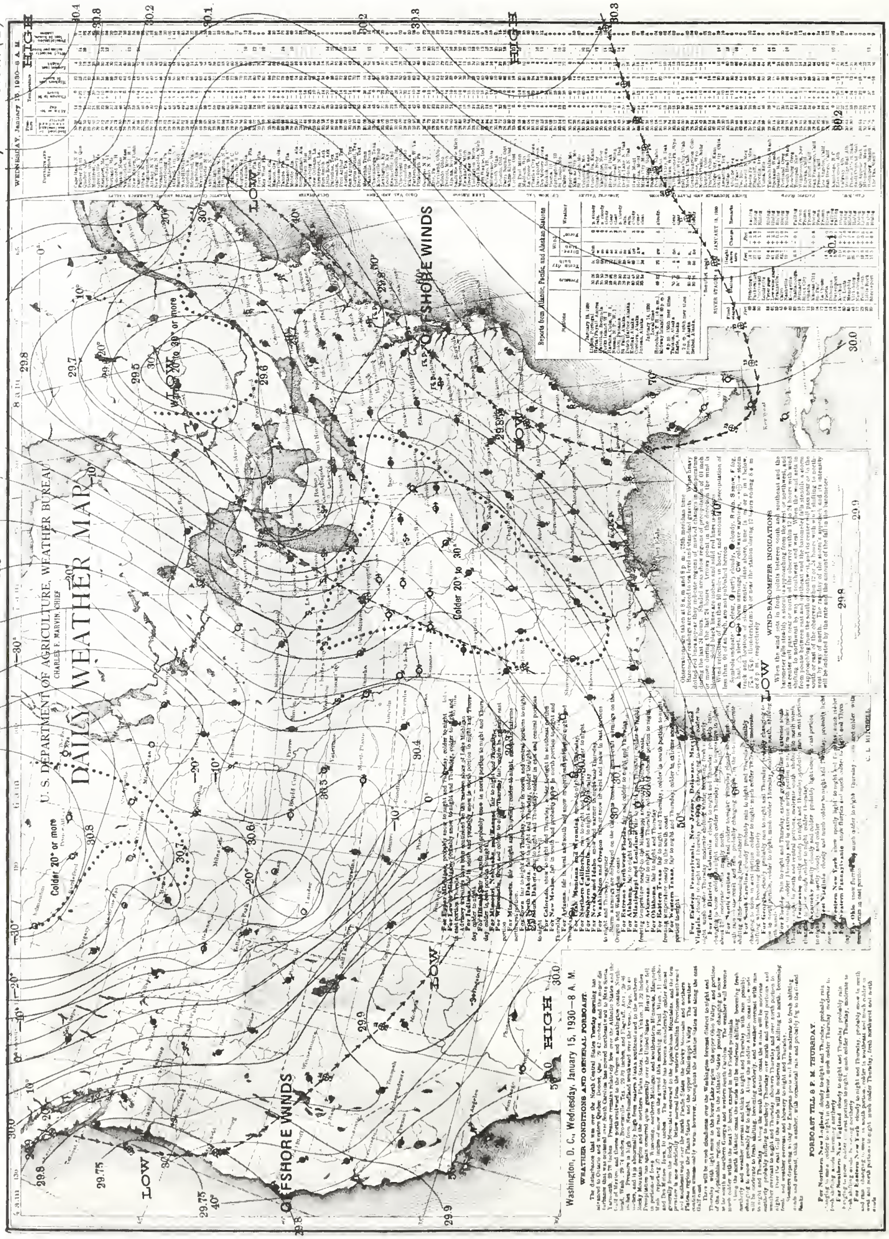

1930 JANUARY 15 8.0h. January 14 18.0h. (2)
157
U.S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
CHARLES F. MARVIN, CHIEF
DAILY WEATHER MAP
HIGH
LOW
OFFSHORE WINDS
OFFSHORE WINDS
Colder 20° or more
Colder 20° to 30° or more
Washington, D. C., Wednesday, January 15, 1930—8 A. M.
WEATHER CONDITIONS AND GENERAL FORECAST
WIND-BAROMETER INDICATIONS

Figure 76

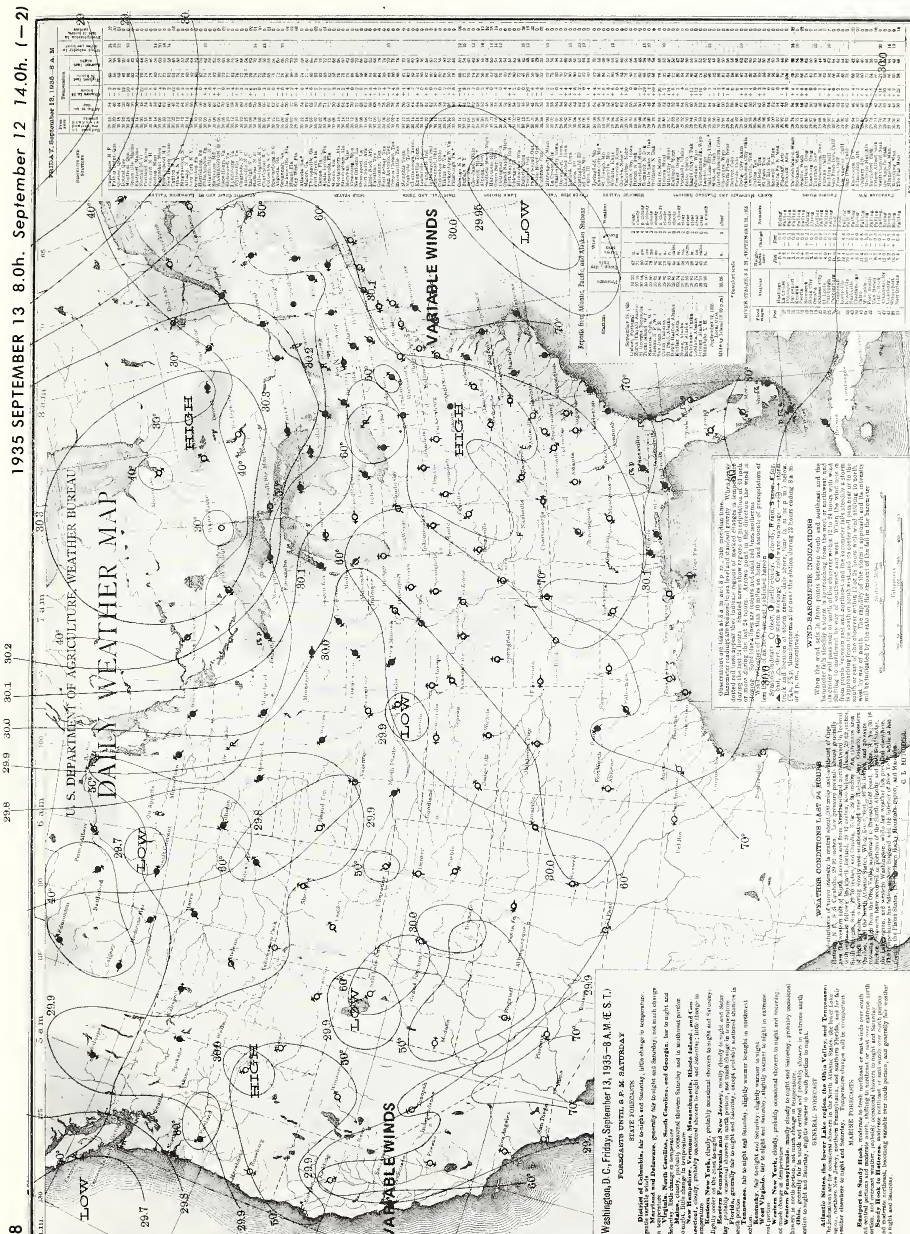

158
1935 SEPTEMBER 13 8.0h. September 12 14.0h. (−2)
U.S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
Washington, D.C., Friday, September 13, 1935—8 A.M. (E.S.T.)
VARIABLE WINDS
HIGH
LOW
WIND-BAROMETER INDICATIONS
WEATHER CONDITIONS LAST 24 HOURS

FIGURE 77

1940 OCTOBER 2 7.5h. October 1 9.5h. (3)

159

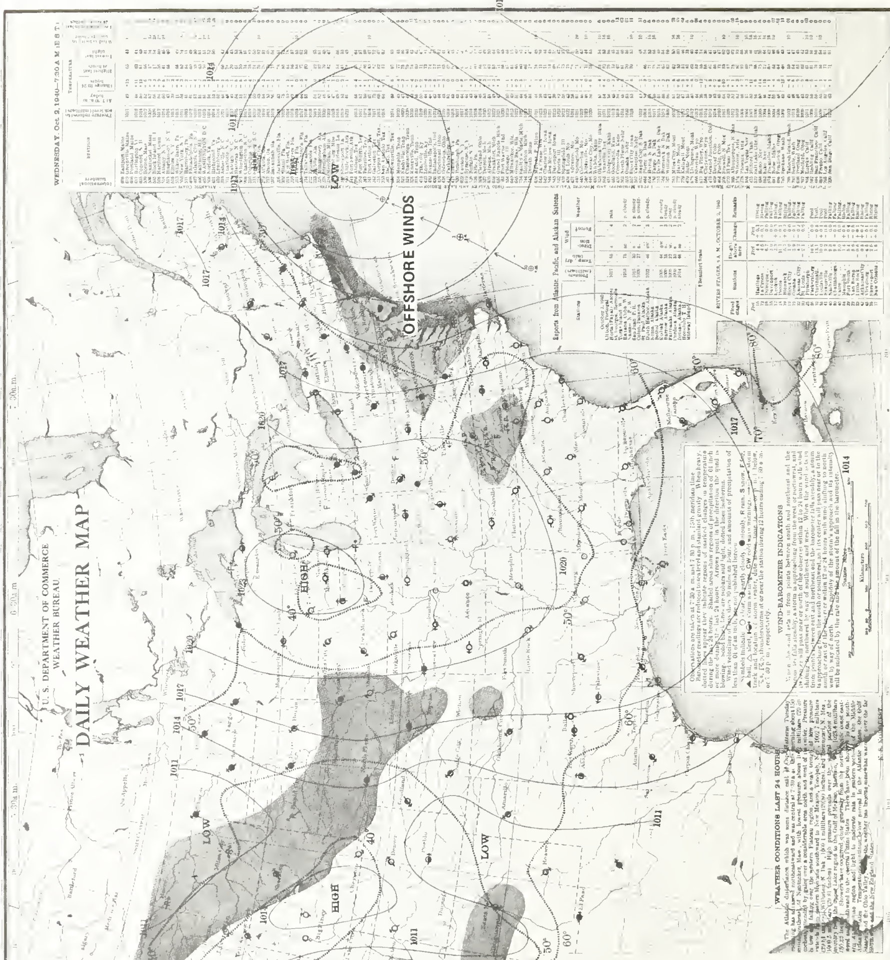
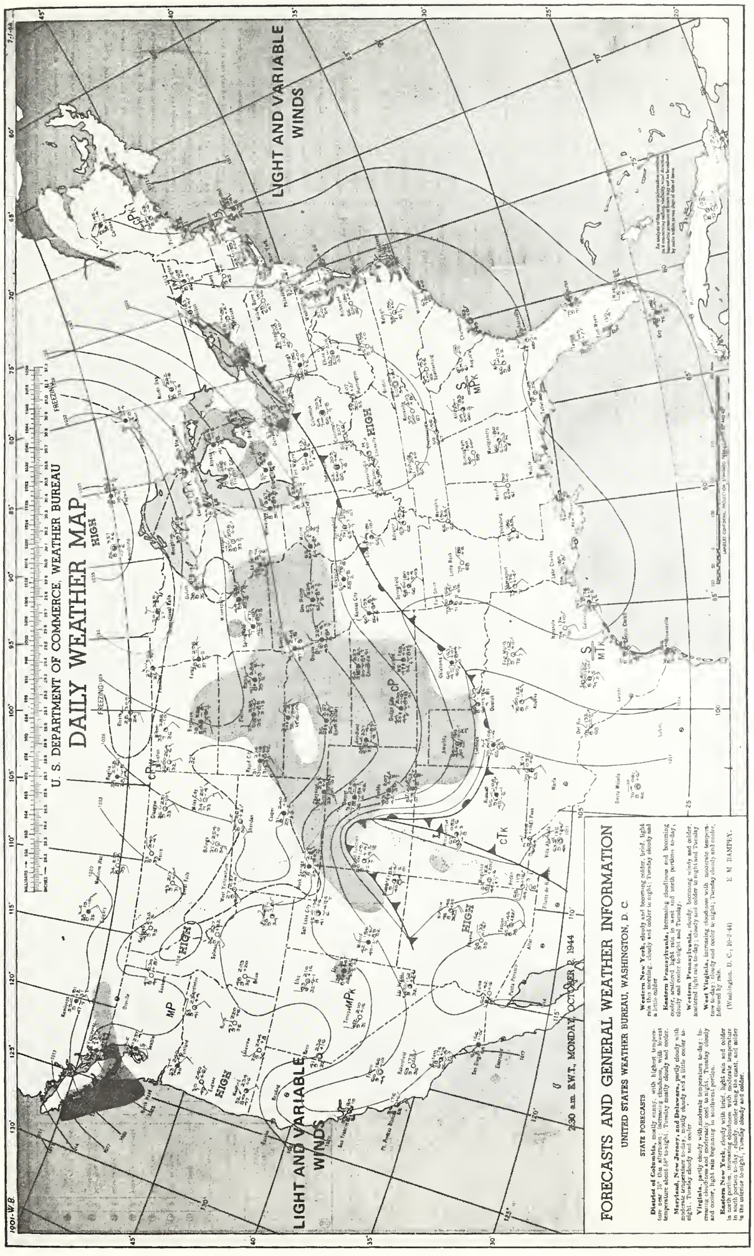


FIGURE 78

1944 OCTOBER 2 1.5h. October 1 17.5h. (−11)



160

FIGURE 79

161 1950 MAY 3 1.5h. May 2 1.0h. (2)

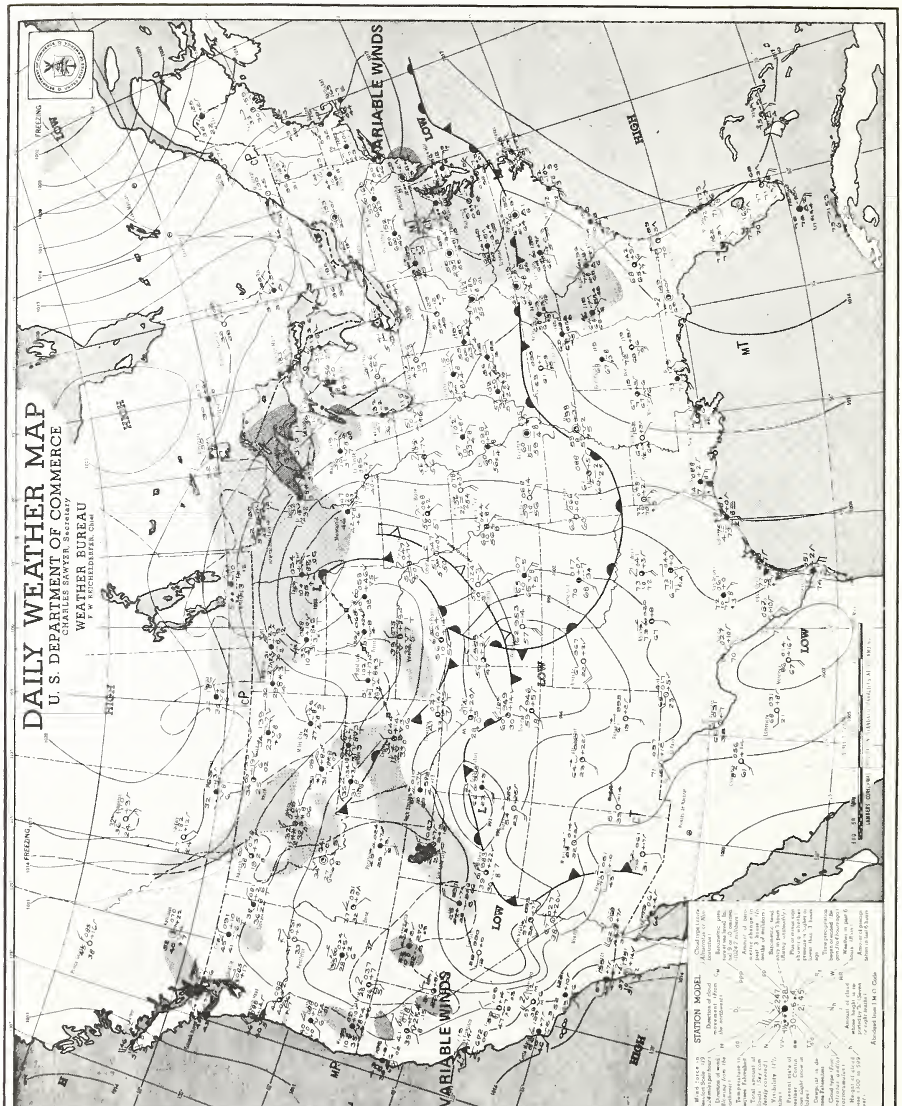


FIGURE 80

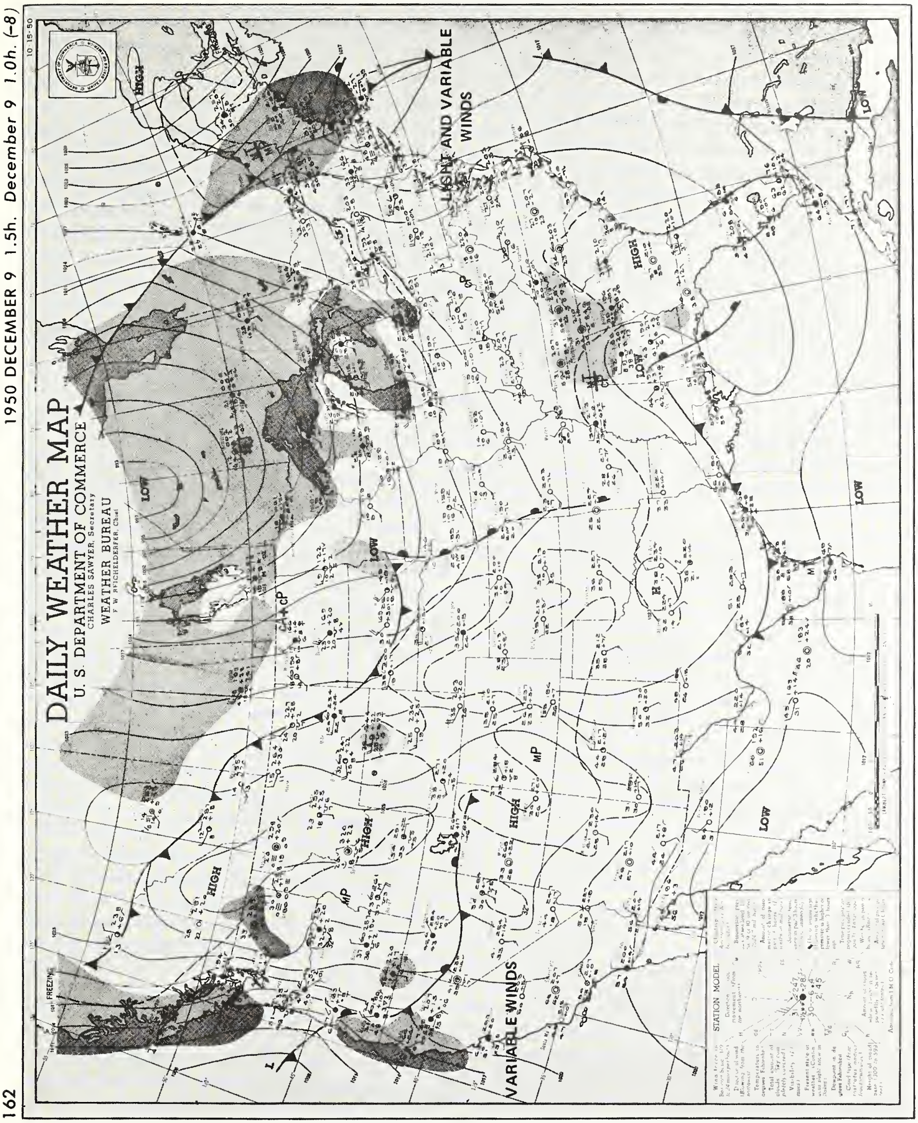

1950 DECEMBER 9 1.5h. December 9 1.0h. (−8)
DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
CHARLES SAWYER, Secretary
WEATHER BUREAU
F. W. REICHELDERFER, Chief
LIGHT AND VARIABLE WINDS
VARIABLE WINDS
HIGH
LOW
STATION MODEL
162

FIGURE 81

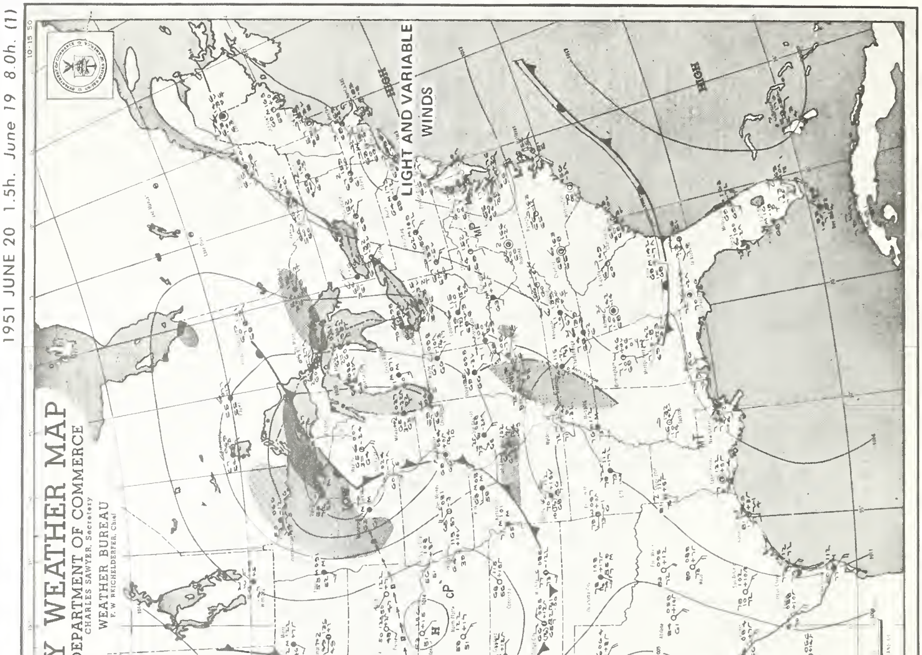

1951 JUNE 20 1.5h. June 19 8.0h. (1)
163
DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
CHARLES SAWYER, Secretary
WEATHER BUREAU
F. W. REICHELDERFER, Chief
LIGHT AND VARIABLE WINDS
VARIABLE WINDS
HIGH
LOW
STATION MODEL

FIGURE 82

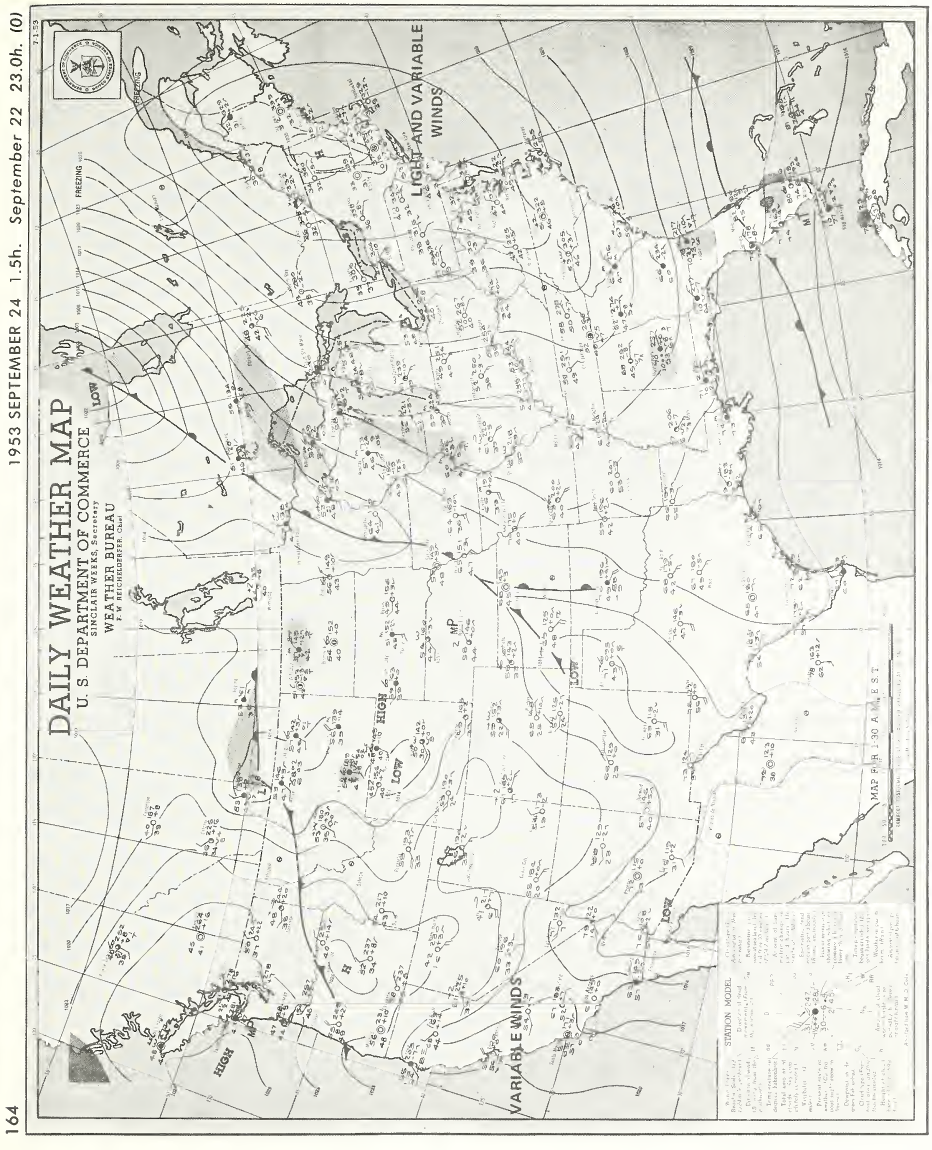
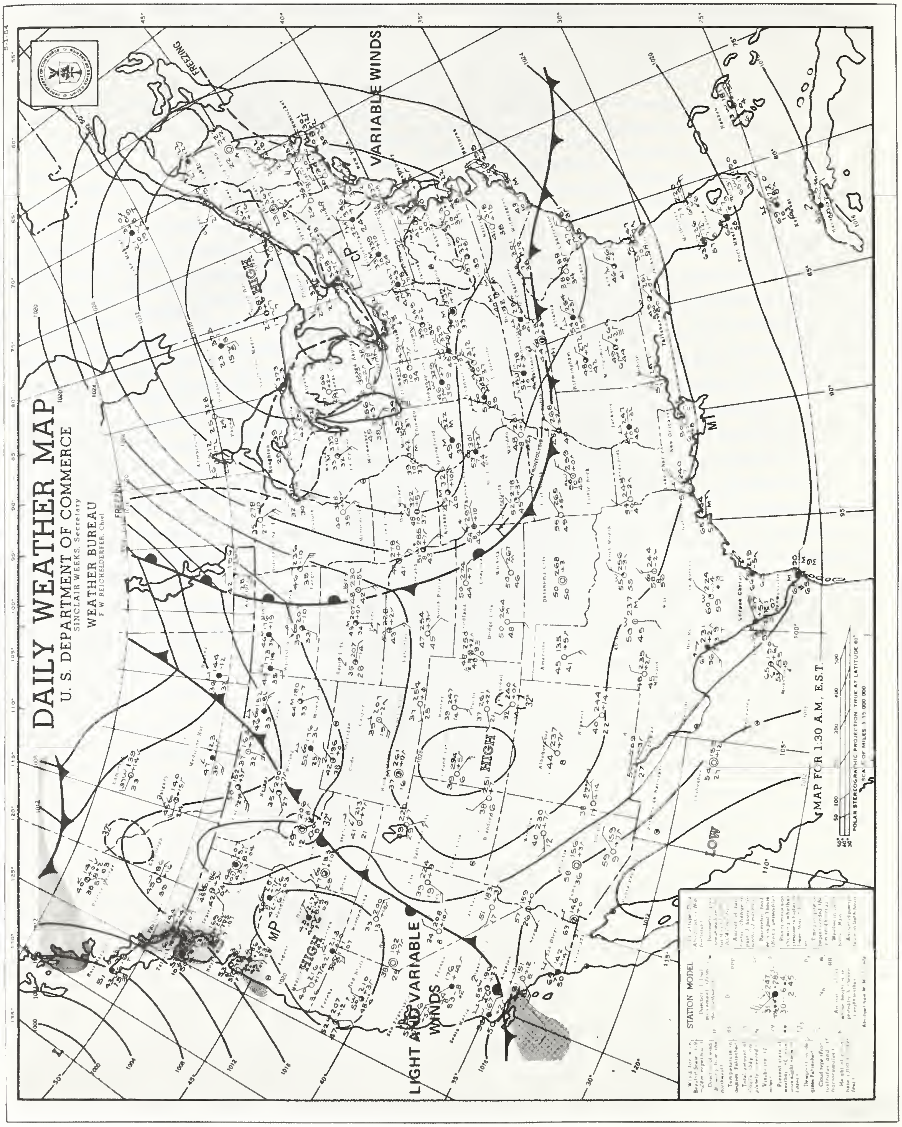

1953 SEPTEMBER 24 1.5h. September 22 23.0h. (0)
DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
SINCLAIR WEEKS, Secretary
WEATHER BUREAU
F. W. REICHELDERFER, Chief
LIGHT AND VARIABLE WINDS
VARIABLE WINDS
HIGH
LOW
STATION MODEL
MAP FOR 1:30 A.M. E.S.T.
164

FIGURE 83

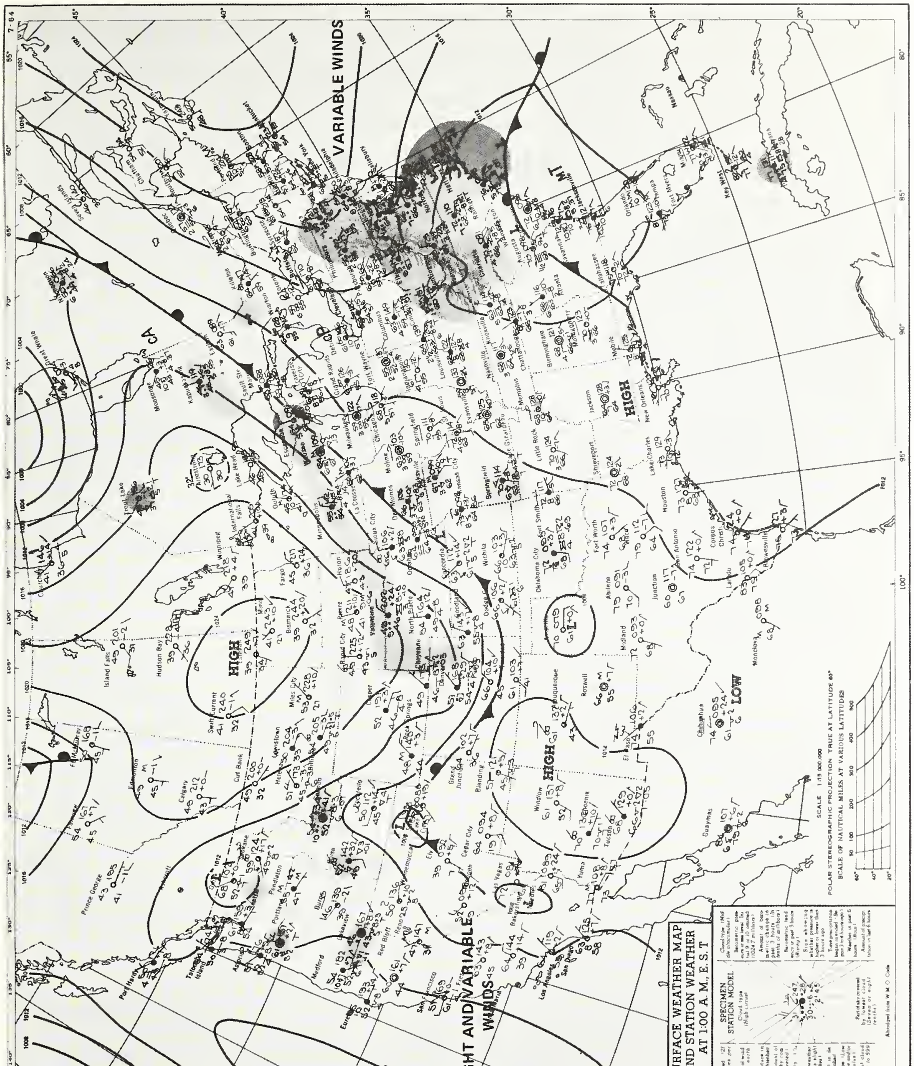
1954 NOVEMBER 10 1.5h. November 10 9.0h. (−1)



165

FIGURE 84

1966 SEPTEMBER 14 1.0h. September 14 13.0h. (−2)



166

FIGURE 85

1967 MARCH 27 1.0h. March 26 0.5h. (5)

167

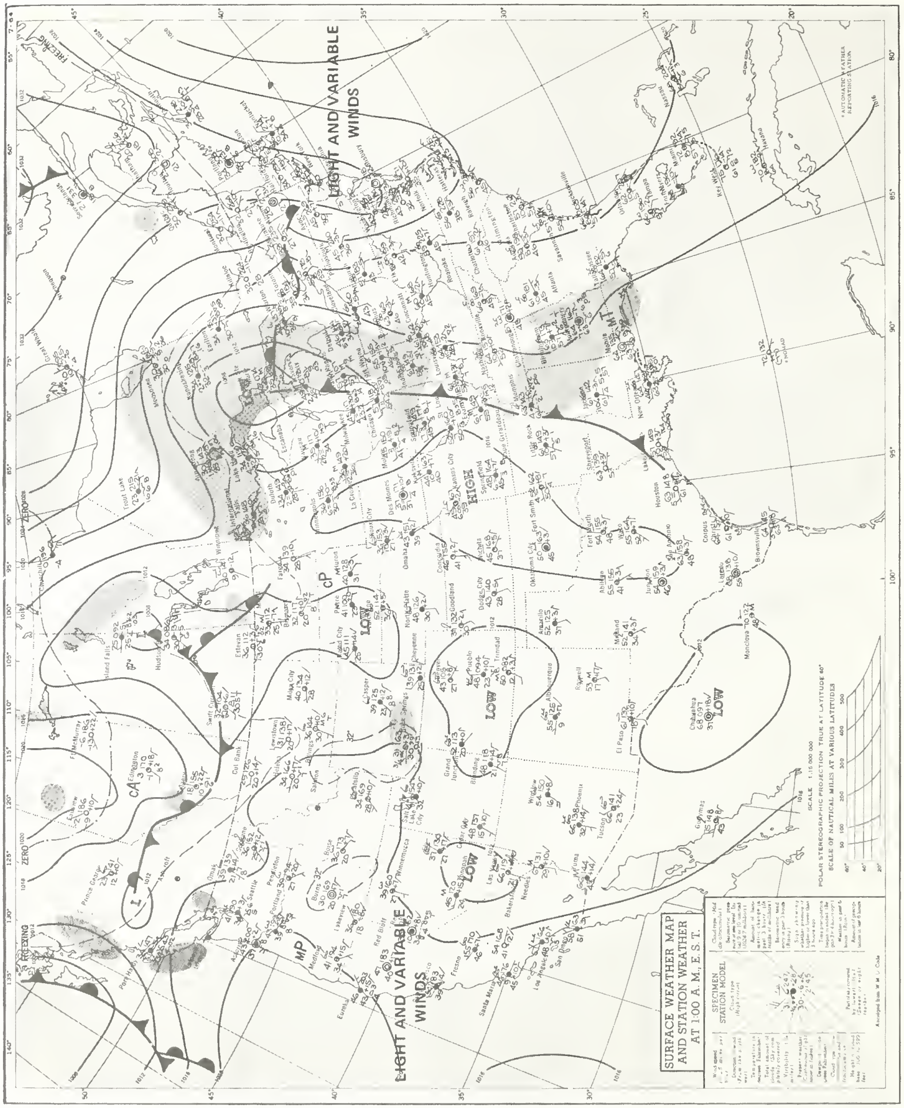


FIGURE 86

168 1968 DECEMBER 19 7.0h. December 19 10.0h. (−6)

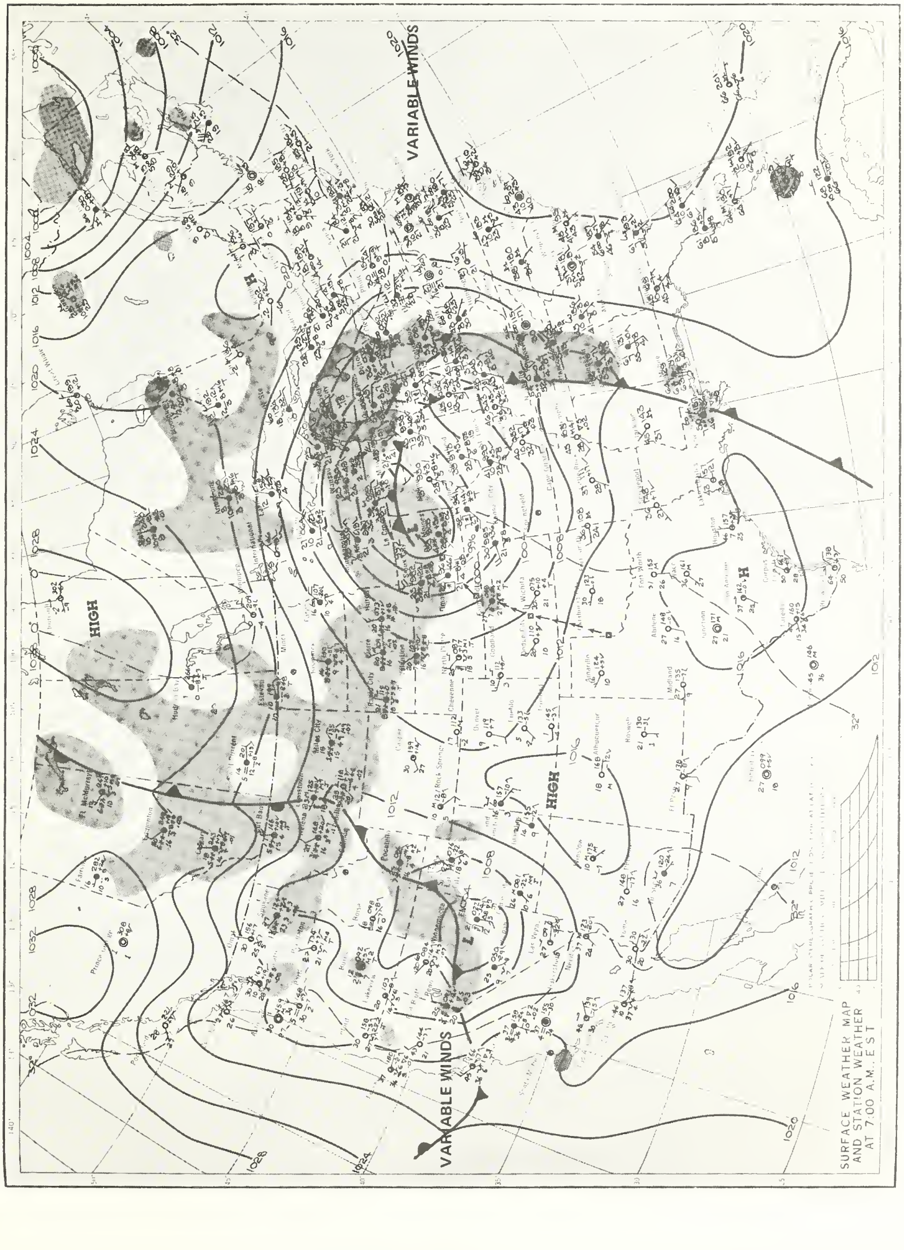


FIGURE 87

1972 DECEMBER 20 7.0h. December 19 18.5h. (−21)

169

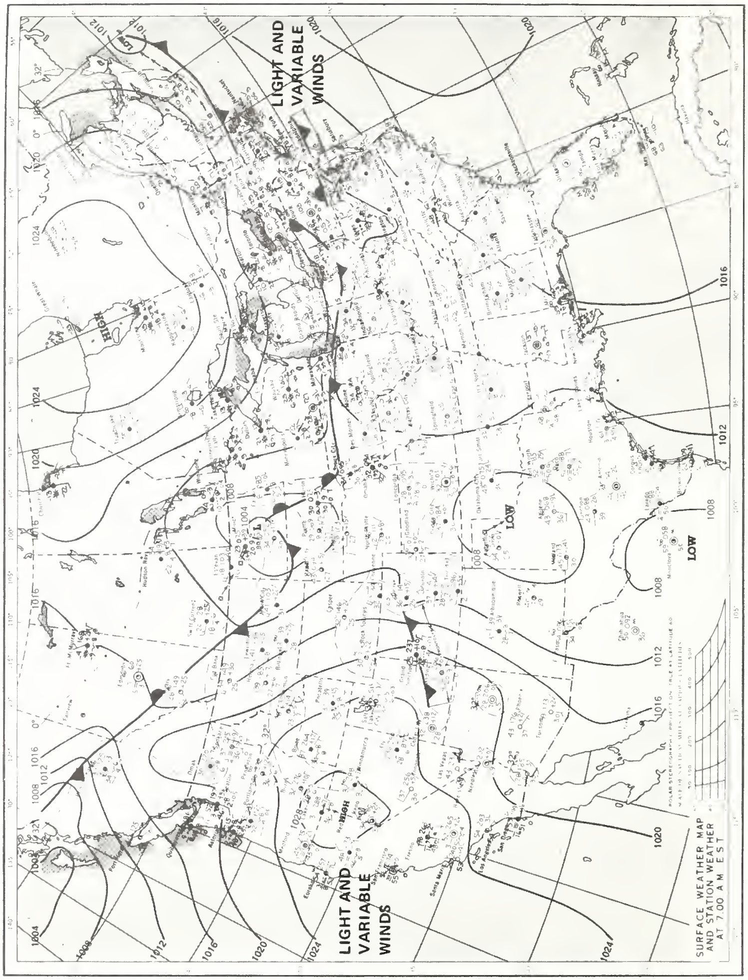


FIGURE 88

170 1974 FEBRUARY 6 7.0h. *February 6 6.0h.* (−24)

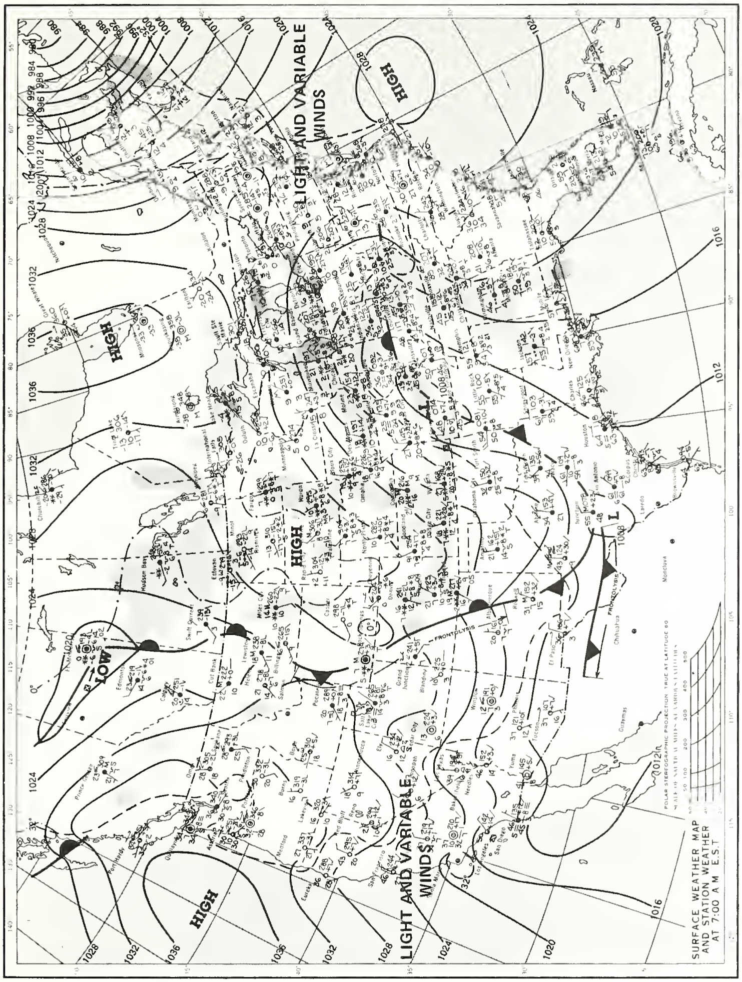


FIGURE 89

TABLE 28a.—*Surface Synoptic Weather Maps for Four Representative Cases of Hurricanes Occurring in Near-Coincidence With Perigean Spring Tides*

Serial No.	Weather map date and mean perigee-syzygy date			Perigee—syzygy (hours)	Region of impact
266	1878	October 23	1. 0h	(−17)	All sections of New England and the mid-Atlantic States, Oct. 23–24, starting off the S.E. coast of Florida and the Carolinas, Oct. 21–23
		October 25	9. 5h		
268	1899	August 20	8. 0h	(−7)	Coasts of Virginia, Delaware, and New Jersey, Aug. 18–19
		August 20	20. 5h		
283	1940	September 2	7. 5h	(+26)	Cape Hatteras, N.C., on Sept. 1, then northeastward to eastern Maine and Nova Scotia
		September 2	12. 0h		
289	1954	October 15 (Hurricane Hazel)	1. 5h	(+21)	Entire mid-Atlantic region and Carolinas, Oct. 15
		October 12	10. 5h		

TABLE 28b.—*Representative Surface Synoptic Weather Map at a Time During Which a Perigean Spring Tide Caused Blocking and Backup of Hydrological Runoff*

Serial No.	Weather map date and mean perigee-syzygy date			Perigee—syzygy (hours)	Region of impact
466	1936	March 21	8. 0h	(+5)	Newburyport and tidewaters of Merrimack River, Mass.
		March 23	1. 5h		

dent. Where supporting winds are present, the vulnerability to tidal flooding on both March 4–5 and April 1 at Willetts Point (and additional east coast locations having similar tidal characteristics) is directly confirmed thereby. The coastline near Boston, Mass. also has been shown to be susceptible to tidal flooding at this time, if subject to the correct meteorological conditions.

As described in the accompanying newspaper account (fig. 95), the combination of both wind and astronomical effects lifted the tides at Boston on 1931 March 4 to an actual height of 13 ft 8 in. The tides at the Naval Yard, Portsmouth, N.H., were raised to a height of 13 ft 10 in. Regional effects of these storm tides occurring near perigee-syzygy are described both in the other news articles reproduced in figs. 95, 96, and in those of table 5, part I, chapter 1.

The circumstance of occurrence of a series of astronomically produced perigean spring tides related in a commensurable pattern to this 1931 March 4 flooding event, each of which was itself accompanied by tidal flooding (Key Nos. 56w, D–57, E–58, 59, and 60) already has been mentioned as of special consequence in reference note 4 supplementing part II, chapter 4. This example of proxigean spring tides therefore substantiates, in every way, the particular influence of such tides in causing coastal flooding when reinforced by the prerequisite wind conditions.

2. The Tidal Flooding of 1939 January 3–5

The next case of coastal flooding to come under consideration from a combined meteorological-astronomical viewpoint—that of 1939 January 3–5 (Key No. F.–68) on the west coast—is notable because of the extent of its occurrence, nearly simultaneously, from Long Beach, Calif., to Aberdeen, Wash. This fact substantiates the effectiveness of perigean spring tides in producing coastal flooding in various latitudes on either the east of west coasts of North America—wherever the correct tidal harmonic constituents, adequate tidal range, a low-lying coastline, and persistent, strong, onshore winds combine to provide the conditions requisite to flooding.

A surface synoptic weather map for the former map plotting time of 0430^h (P.s.t.) on 1939 January 4 is included among the group of maps following table 26. As indicated by the several newspaper accounts of this flooding event which appear below and in table 5, part I, chap-

1878 OCTOBER 23 1.0h. October 25 9.5h. (−17)

266

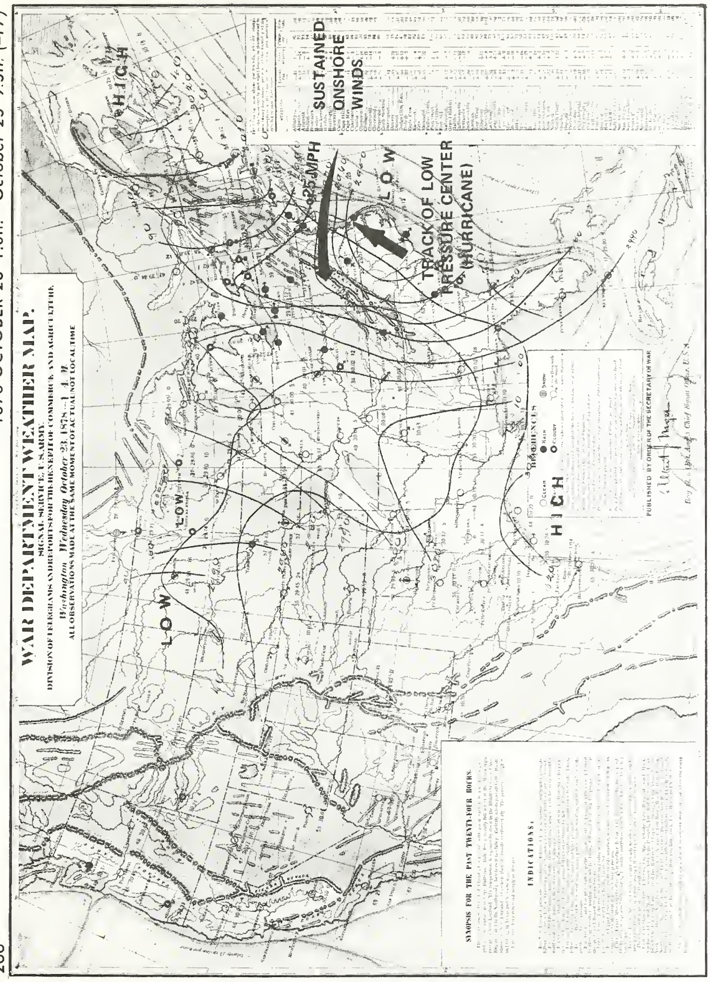


FIGURE 90

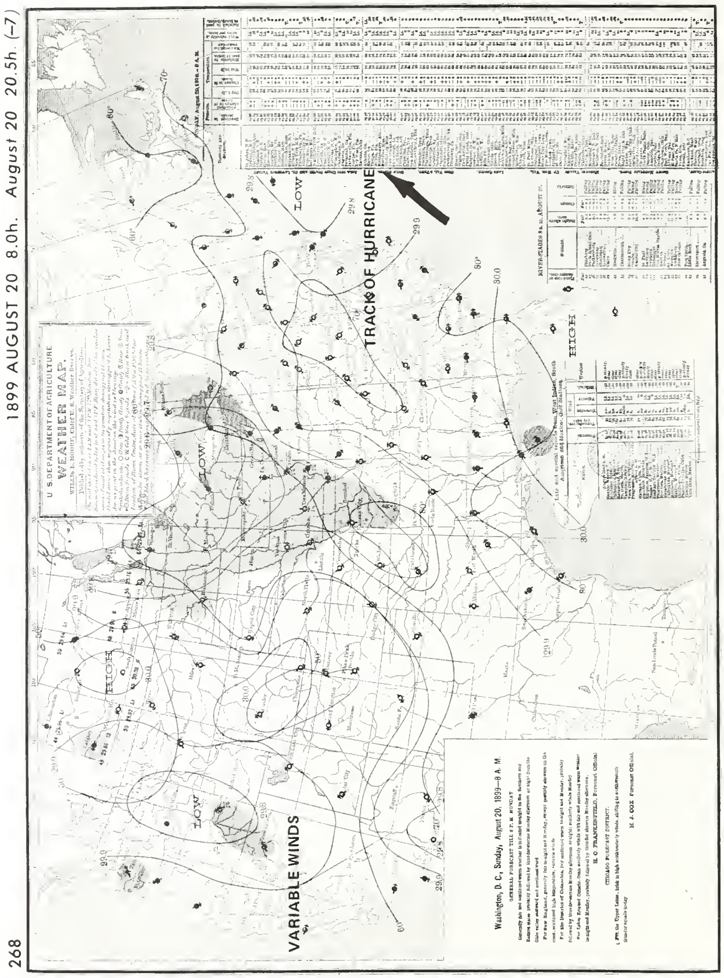

1899 AUGUST 20 8.0h. August 20 20.5h (–7)
268
U.S. DEPARTMENT OF AGRICULTURE
WEATHER MAP.
TRACK OF HURRICANE
VARIABLE WINDS
HIGH
LOW
Washington, D.C., Sunday, August 20, 1899—8 A.M.

FIGURE 91


1940 SEPTEMBER 2 7.5h. September 2 12.0h. (26)
283
U.S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS
TRACK OF HURRICANE
VARIABLE WINDS
HIGH
LOW
Washington, D. C., Monday, September 2, 1940

FIGURE 92

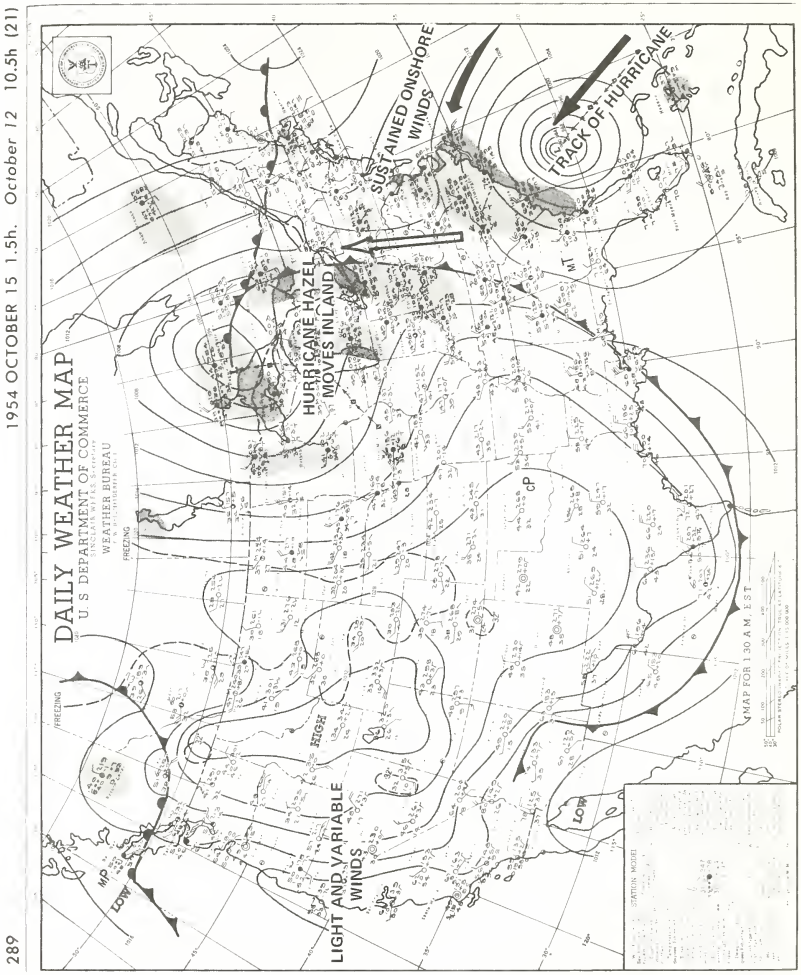

289
1954 OCTOBER 15 1.5h. October 12 10.5h (21)
DAILY WEATHER MAP
U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
SUSTAINED ONSHORE WINDS
TRACK OF HURRICANE
HURRICANE HAZEL MOVES INLAND
LIGHT AND VARIABLE WINDS
HIGH
LOW
LOW
MAP FOR 1 30 A M, E S T
STATION MODEL

FIGURE 93

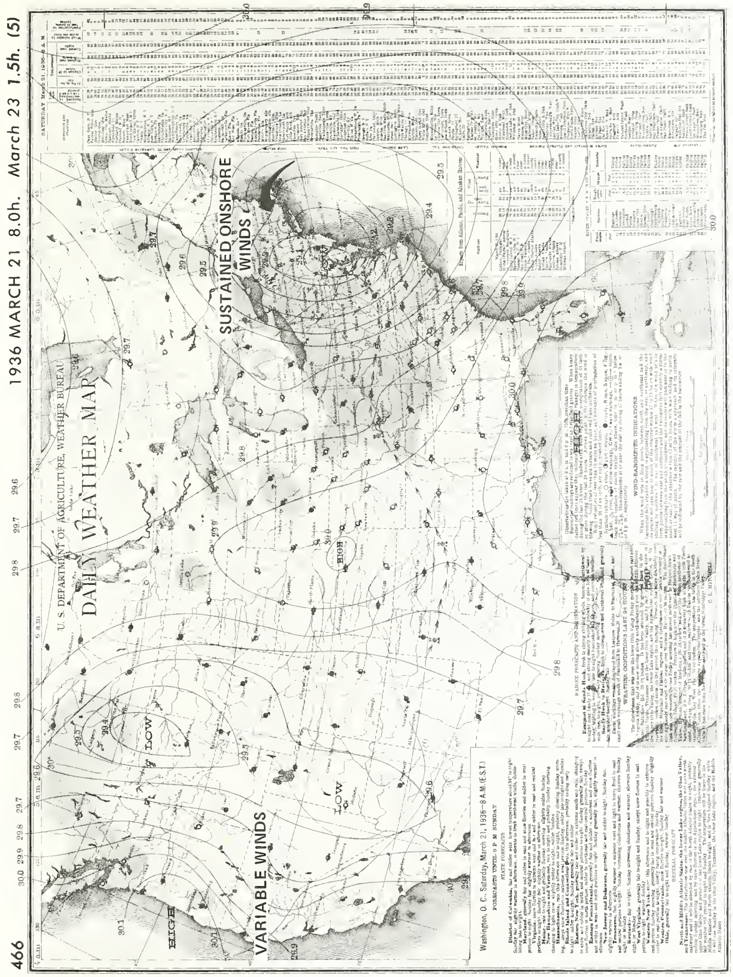

466
1936 MARCH 21 8.0h. March 23 1.5h. (5)
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU
DAILY WEATHER MAP
SUSTAINED ONSHORE WINDS
VARIABLE WINDS
HIGH
LOW
Washington, D. C., Saturday, March 21, 1936—8 A.M. (E.S.T.)

FIGURE 94

The New York Times
Thurs., March 5, 1931
Page 20, Cols. 3–6

SEABOARD IS LASHED BY TIDE AND STORM

Tide and storm had an interesting history, with the Weather Bureau acting as recorder. It appears that on the night of Feb. 27 a little storm was cradled out in the open spaces of Utah. At first it tried its comparatively puny strength on the northeastern part of Mexico, whooped it up over the Gulf of Mexico and made a vicious turn toward Tampa, reaching there Monday morning.

Takes to the Atlantic.

Here it developed an extremely violent temper and began to vent its wrath on the Atlantic. By Tuesday morning it had arrived at Cape Hatteras, rolling tremendous waves before it, toward the shore, from points as far as 1,000 miles out. Rushing northeast while growing to a sixty-mile gale, it worked all Tuesday night and yesterday morning, driving the foaming green water toward the coast.

This continued drive from the east would ordinarily have been enough to create a high tide, but to make matters worse, the moon is at full, exerting its maximum strength on the ocean. Thus, between the two, New York, New Jersey and other coastal States felt the power of the worst tide in four years . . .

New Jersey Resorts Battered.

Atlantic City, Margate, Ventnor City, Ocean City and Sea Isle City received a tremendous battering from the tide and reported heavy damage. Rushing into the inlet and thoroughfare the waters spread out over the long meadows back of Atlantic City, until they were completely submerged. Only the shore line trolley tracks remained clear. In Longport and the inlet district the water was six inches deep in the streets, marooning families in their cottages and sloshing into cellars everywhere . . .

In New York Harbor not only the ferryboats but the large ocean liners were affected. Commuters were delayed while the ferryboats maneuvered for the best position for the placing of gangplanks, and on the New Jersey side of the Hudson the tide was so high that passengers had to splash through several inches of water. Behind the Erie station in Jersey City automobiles and persons on foot virtually had to ford their way to cross the streets.

When the giant liner Europa docked yesterday morning at the army base pier, foot of Fifty-eighth Street, Brooklyn, she was so high over the pier that the gangplank, when put down, was tilted at a crazy angle . . .

. . . Last night remote shore villages in New Jersey and on Long Island were still sending in reports of floods in the streets, boats carried to sea and homes undermined by the tide . . .

. . . EAST HAMPTON, L. I., March 4.—Ring Lardner's Summer home on the dunes here was hanging over the cliff tonight after the high tide had undermined the house. It is feared that the house will topple into the sea if a heavy tide rolls in tomorrow . . .

HEAVY DAMAGE AT BOSTON

Loss From Flood and Waves Said to Be Enormous.

BOSTON, Mass., March 4.—A huge tide driven to heights unprecedented in two decades lashed the shores of New England today, causing havoc among shore cottages, demolishing sea walls and rolling up a damage which could not be estimated. The tide rose three feet above normal.

Eighty-two structures were damaged in Revere alone, seven of them being completely wrecked and washed away. Seas rolling through carried away all cottages, furniture, ripped up floors and undermined foundations. Damage at Revere was estimated at $1,000,000. At Roughan's Point, in the Beachmont section, cottages were loosed from their locations and floated together like packing boxes . . .

. . . The Revere Beach & Boston suspended operations for an hour before and nearly two hours after high water, at 11 o'clock. Two East Boston lines of the elevated were suspended for a time. The Portland division of the Boston & Maine was held up nearly two hours by tracks under water. Sections of the New Haven tracks were washed out between Neponset and Milton, and between Norfolk Downs and Atlantic. All communication between Lynn and Boston was suspended during the flood tide. Whole sections of rail were under water. Shore roads, washed by seas or flooded entirely by the record tide, were left impassable because of debris when the waters receded . . .

. . . Today's tide went to a height of 13 feet 8 inches . . .

. . . From everywhere came reports of the appearance of myriads of sea rats, driven out of the burrows near normal high tide marks by the rising flood.

At Portsmouth Navy Yard the highest level ever recorded was reported, 13 feet 10 inches . . .

. . . At Newburyport the 30,000 clam purification plant was undermined by rushing high water and nearly wrecked. At Salisbury, cement walks and miles of boardwalk along the beach were washed away. Nahant was turned into an island. Everywhere boat yards were endangered . . .

. . . At Hingham thousands of feet of lumber floated to sea when the yards of J. H. Kimball & Co. and of E. E. Whitney were flooded to the tops of the piled boards. At Yarmouth, the town bathhouse, town pavilion and town dock were distributed over several back yards.

With half of the Nantasket Beach Railway undermined and destroyed, with practically every cottage and Summer residence on the ocean side of the Nantasket peninsula damaged and with Hull cut off from communication, damage from Nantasket to Pemberton was estimated at more than $1,000,000.

Gloucester suffered more heavily than at any time within recent years, with waterfront streets submerged, train service completely cut off and cellars flooded. No trains operated between 9 A. M. and 5:50 P. M. At Rockport a heavy surf washed away the new sea wall completed a few months ago.

CITY OF LYNN IS ISOLATED

LYNN, Mass., March 4 (AP).—Lynn was virtually isolated by the storm and tide. Transportation lines were paralyzed. The harbor front was flooded. Children were taken from a flood-surrounded school in ambulances.

The adjacent town of Nahant was made an island when the ocean waters rose above the isthmus for the first time since 1909. The high waters swept into Lynn sewers and breaking waves sent water bursting out of manholes like geysers . . .

. . . At Swampscott, adjoining Lynn on the north, the tide swept in over shore roads, bringing up dories and fishing equipment with it.

1931 Mar. 4
5.5h e.s.t. (0)

D–57

The New York Times
Mon., March 9, 1931
Page 1, Cols. 1, 2

HIGH SEAS BATTER COAST

HIGH TIDES LASH BEACHES

In and about New York a high wind that accompanied heavy rains and a high tide caused at least seven deaths, scores of injuries and millions in property damage . . .

Figure 95. Newspaper articles in connection with the 1931 March 4–5 tidal flooding in New England.

METROPOLITAN AREA HIT HARD

At least seven deaths, millions of dollars in property loss and scores of injuries were caused by the gale that scourged New York and New Jersey Saturday night and all day yesterday.

The gale, as earlier in the week, was assisted by the waning moon, in rolling up tremendous tides that gnawed away long stretches of waterfront, undermined Summer homes and flooded streets and highways . . .

. . . at the Battery the tide rose to within a foot of the top of the sea-wall for the first time in many years . . .

1931 Mar. 4
5.5h e.s.t. (0)
D–57

D-57 (a), E-58 (a)

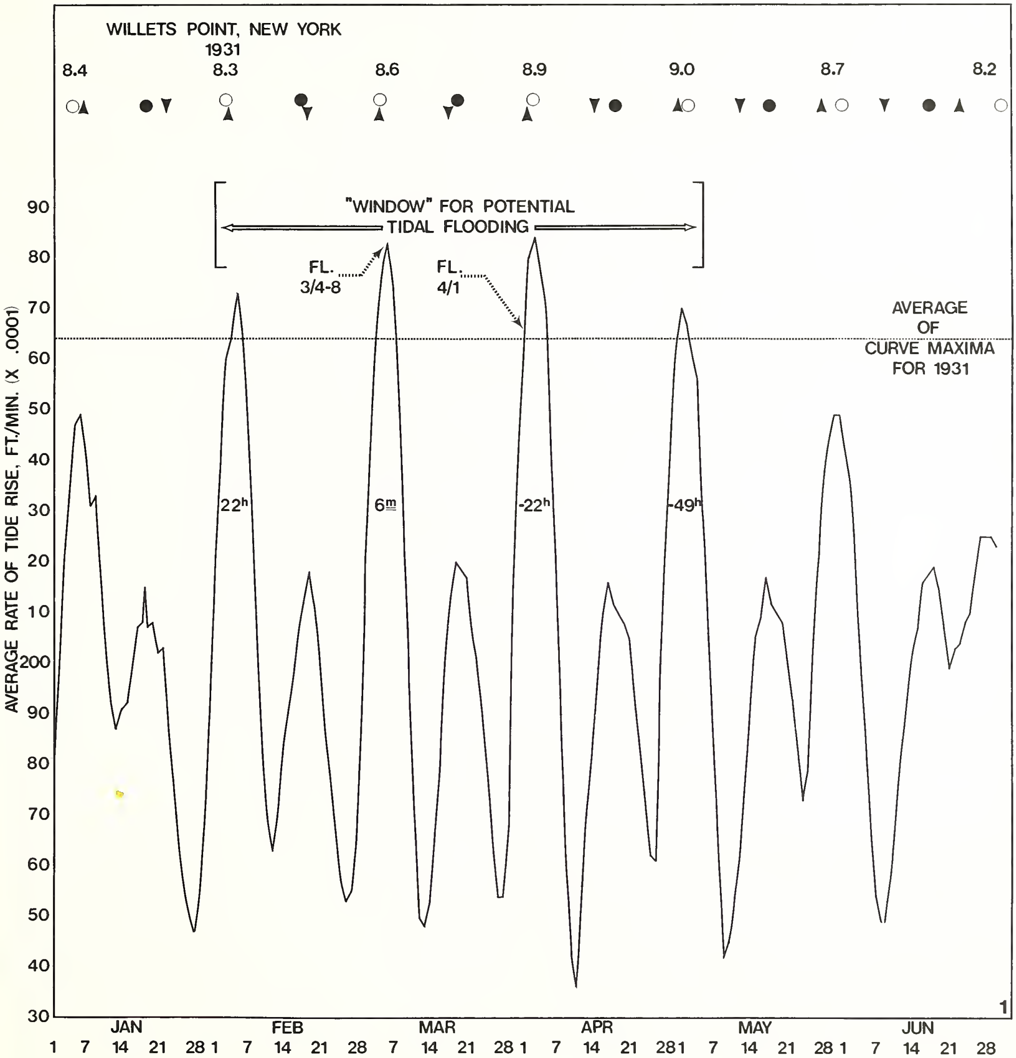


FIGURE 96.—Continuation of newspaper items relative to 1931 March 4–5 tidal flooding event. The appended graph also shows the accelerated rate of astronomical tide growth accompanying this event. The tidal enhancement is associated with an alignment of perigee-syzygy within 6 minutes at the mean epoch of 1931 March 4.23 e.s.t. (See pt. II, ch. 8 for an explanation of these curves indicating rate of tide rise.)

ter 1, tidal flooding of major consequence had begun along the Washington and Oregon coasts as early as January 3. However, this weather map for the very next day, midway in the tidal flooding period, reveals no deep low pressure system, intense precipitation pattern, strong winds, or other active weather indicators either along the coast or offshore. Despite this, the tidal flooding was continuing along the Washington coast and beginning in southern California. (It is important to remember in this connection that atmospheric fronts were not introduced on official U.S. Weather Bureau synoptic weather maps until August 1, 1941.)

The general summary of weather conditions over this Pacific coast region appearing in the *Monthly Weather Review* for January 1939 solves the mystery of the meteorological contribution to this tidal flooding event. The answer is inherent within a circumstance which occurs often along the Pacific coast of North America, but which (before satellite weather photographs became available) confounded many an early weather forecaster in this area attempting to determine the cause of such surging uplifts of water along the coastline—determined as not due to seismic sea waves (known alternatively as *tsunamis*). (Cf., for example, Key No. 64 in table 5.)

A contributing element to such coastal inundations, especially at times of perigean spring tides, can lie in deep atmospheric low pressure systems existing possibly many hundreds of miles at sea. These low pressure systems, with their associated steep atmospheric pressure gradients, produce very strong surface winds. The winds, in turn, generate an active swell on the sea surface. The speed of movement of such a deep low pressure system can far exceed that of the swell it generates. Thus the low pressure center, accompanied by strong winds, can move rapidly onshore and be out of the area before the swell ever reaches the coast. Conversely, a strong high pressure system can block the forward movement of a low pressure cell. As a result, the swell which the latter has produced is propagated along the sea surface and may strike the coastline while the low center maintains its position many hundreds of miles at sea.

In either case, if a very strong swell arrives along the coastline at the same time that perigean spring tides rise to their greatest levels at high water, the reinforcing action between strong swell and augmented tides can only cause tidal flooding—while the apparent cause (lacking immediate strong winds) remains obscure. The present instance of coastal flooding seems to have involved both circumstances, the first over Washington and the second in southern California. (See fig. 97).

Numerous other examples of each type are contained among the newspaper accounts of tidal floodings along both the east and west coasts contained in table 5. On certain parts of the California coastline, notably from Point Conception south, a frequently observed tendency exists for a channeling of a northeasterly directed swell—apparently by similarly oriented bathymetric configurations on the ocean floor. This influence has been variously noted by marine engineers writing in *Shore and Beach* magazine [1], by coastal resource engineers in the Los Angeles District Office of the U.S. Corps of Engineers, and by a beachguard with many years of observational experience at Imperial Beach, Calif.

The effects of the strong swell generated by a hurricane located even far to the southwest in the subtropical regions of the Pacific can sometimes be felt as an active series of ocean surges impacting on the California shoreline. The swell may appear in an otherwise calm sea, unswept by wind or waves, under a perfectly clear sky, and with no visible generating source, having been propagated from its distant origin, losing little in flooding potential on the way.

From an astronomical viewpoint, while the perigee−syzygy alignment ($+14^h$) which produced the perigean spring tides in case F–68 was not nearly so precise as in case D–57, the astronomical high tides resulting were of considerably augmented amplitude and range with respect to their average values.

On 1939 January 5 at 0802^h (P.s.t.), for example, the predicted higher high water at Los Angeles (Outer Harbor) was 7.0 ft. The predicted maximum tidal range for this same date was 8.6 ft. The latter value is significantly in excess of either the diurnal range (that between mean lower low water and mean higher high water) of 5.4 ft or the mean tidal range of 3.8 ft at Los Angeles.

At Aberdeen, Wash., the HHW predicted to occur at 1218^h (P.s.t.) on January 5 was 11.2 ft and the predicted maximum range for this date was 12.7 ft. By contrast, the diurnal range at Aberdeen is only 9.9 ft.

At Astoria (Tongue Point), Oreg., the HHW predicted for 1233^h (P.s.t.) on January 5 was 9.8 ft and the maximum range 11.2 ft, whereas the diurnal range at Astoria is only 8.1 ft. These unusual tidal elevations, combined with the reinforcing influence of strong onshore winds, resulting high seas, and ground swell confirmed by the following general weather summary, could only produce

The Oregon Daily Journal
Fri., Jan. 6, 1939
Page 1, Col. 7

Sea Unruly in California

Three Homes Washed Into Pacific; Others Damaged

Long Beach, Cal., Jan. 6—(AP)—Three modest beach homes in the Alamitos peninsula area southeast of Belmont shore were washed to sea today as giant breakers, riding in from the Pacific on high tide ground swells, crashed over the low sea wall . . .

. . . The tide also brought extensive damage to Manhattan and Hermosa beaches, where the highest water in years flowed as far as 180 feet inland.

But the Alamitos peninsula below Long Beach was hardest hit.

William E. Ross, boat builder there, said the tide was the worst in his 35 years' experience.

Mrs. D. H. Collins stood by and watched the tide carry her two-story dwelling into the Pacific . . .

. . . More than two feet of water roared in at some Santa Monica bay points, sweeping out the board walk along the strand between Manhattan and Hermosa beaches . . .

Tillamook Area Raked By Sea Surge

Wheeler, Jan. 6.—Devastation was left by surging seas that hit Tillamook county beaches Thursday noon. High water marks were broken. The Southern Pacific track at Barview, washed out Tuesday and repaired Wednesday, was torn from the roadbed and rails and ties strewn along the Coast highway . . .

. . . The seawall was washed inland 50 to 250 feet from Manhattan to Barview . . .

13-Foot Tide Recorded at Newport

Newport, Jan. 6.—A 13-foot tide, one of the highest ever recorded here, washed the water fronts Thursday. Yaquina Bay was covered with heavy logs and timbers, kept moving away from boats and buildings by coastguardsmen . . .

. . . Several hundred feet of the trestle work of both jetties left standing by former contractors was washed to sea . . .

. . . The surging breakers cut off lights, water and traffic from the Bayocean peninsula and washed out the highway at Oceanview, marooning those on the peninsula. The surf almost demolished the seawalls at Netarts . . .

1939 Jan. 5
20h P.s.t. (+14)

F–68

Figure 97.—Representative news articles relative to the tidal flooding of 1939 January 3–5 occurring in Washington, Oregon, and southern California.

the damaging tidal flooding along the coast which took place.

From: *Monthly Weather Review,* Vol. 67, No. 1, January 1939

F–68—Coastal Flooding of 1939 January 5, Central Oregon to Southern California

"The early part of January may be characterized as one of the stormiest periods in recent years on the North Pacific Ocean. At the opening of the month low pressure extended across the northern half of the ocean, with three distinct and powerful centers, one east of Japan, another in upper middle longitudes, and a third off the west coast of the United States and British Columbia. In connection with these specific storms and the generally unsettled weather existing generally to the northward of the 30th parallel during the 1st to 5th, gales, many of which were of hurricane or near hurricane intensity, occurred over wide areas, some being experienced almost as far south as the 25th parallel. However, in east longitudes, the greater part of the high winds reported occurred between latitudes 30° and 45°N., and in west longitudes, between 35° and 45°N., except along the American coast, where they were experienced also in much higher latitudes.

"The easternmost Pacific storm was of unusual severity. It was damaging on the Washington, Oregon, and California coast, from the standpoint of both heavy winds and high seas, which continued with varying intensity from the 1st to the 5th. At the entrance of the Strait of Juan de Fuca, the Swiftsure Bank Lightship reported winds of forces 9 to 10 on the 1st, 2d, and 4th. At sea several vessels were delayed in passage, and a number of passengers on the American steamship *Lurline* were injured, according to press reports, when a huge sea swept the decks. The American steamship *Mauna Ala* reported southerly winds of forces 11 to 12 on the 2d and 4th while proceeding southwestward some 100 to 200 or more miles west of the Oregon coast, lowest barometer 29.08 inches, on the 2d. Much farther at sea, near 43°N., 148°W. the Japanese motorship *Genyo Maru* encountered strong gales to hurricane winds, lowest barometer 28.71, on the 3d."

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3. The Coastal Flooding of 1959 December 29–30

This case of coastal flooding (I–83e,w) is the first among the present examples for which specialized information as compiled in the U.S. Weather Bureau (now the National Weather Service) publication *Storm Data* is available. It also provides an example of two nearly concurrent tidal floodings which resulted from perigean spring tides produced on both the east and west coasts of North America. Although the respective floodings on opposite coasts were separated by a day, in each case the event was a function of strong onshore winds acting upon the astronomically produced perigean spring tides. Other such instances of near-simultaneous tidal flooding on both coasts exist in Key Nos. 56e,w, 84e,w, L–93e,w, and M–98e,w. (See table 1.)

A surface synoptic weather map plotted for 1959 December 29 at 0100^h (e.s.t.) is included among the group of maps following table 26. This map clearly shows that the meteorological factor which contributed to the east coast tidal flooding was a large low pressure system with two centers located just inland from the mid-Atlantic coastline. The easternmost of these two centers contained a nonoccluded frontal wave. The peak of this wave was centered, at map time, over the Delmarva Peninsula, with its warm-front portion extending east-northeast along the entire southern New England coast. This resulted in a strong wind circulation from the east-northeast and hence directly onshore from the sea at coastal points to the north of the front—a typical setup condition for the familiar New England nor'easter in winter.

The effect upon the rising perigean spring tides, whose mean epoch occurred on 1959 December 29 at 0500^h (e.s.t.) was also typical. Tidal flooding ranged along the coast from New Hampshire to Maine. The severe magnitude of this tidal flooding and the associated damage in New Hampshire, Massachusetts, and Maine are described in the following summaries from *Storm Data*. Further information is available in the accompanying newspaper articles (fig. 98), with an additional news account appearing in table 5. Considerable data in connection with this instance of coastal flooding, an event described by the U.S. Coast and Geodetic Survey as produced by "the

The Boston Herald Wed., Dec. 30, 1959 Page C3, Cols. 2–4, 6–8 *1959 Dec. 29 5h e.s.t. (−18)* **I–83e**

South Shore Areas Lose Power; Streets Flooded

A 100-foot section of the seawall at Lighthouse Point, near Rebecca road where the Italian freighter Etrusco went aground in 1956 was washed away and homes on the point were isolated for several hours.

Stores in the Scituate Harbor area were flooded, with a foot of water pouring both in and out of the First National Store on Front street. The street, main business thoroughfare, was closed during the morning.

In Marshfield, 50 families were evacuated for several hours from the beach areas at Rexhame, Ocean Bluff, Brant Rock and Green Harbor.

DIKE GIVES WAY

The situation was particularly tense in the Brant Rock area where the famed esplanade was under three feet of water after a dike on the Green Harbor River gave way at 11 a.m. . . .

Northeaster Lashes All Cape Cod

15-Foot Tides Smash Provincetown, Barnstable

Storm tides 15 feet high crashed across waterfronts of Provincetown and Barnstable while the whole Cape Cod area was lashed with a heavy rain driven by northeast gale winds.

Peak of the flood tides hit at 11 a.m. and flooded scores of cellars in both towns and washed out stretches of some highways and made others impassable for several hours.

VILLAGE THREATENED

In Barnstable the sea flooded to within 50 yards of the main street of Barnstable Village. In Provincetown, Commercial street was hip-deep at one point and a number of stores and dwellings were damaged.

Both Barnstable and Provincetown police estimated damage in the thousands of dollars but no injuries were reported.

Police and firefighters stood by to evacuate 60 families in the Common Field area of Barnstable as water flooded Commerce road and isolated a big freezing plant. The water receded before evacuation became necessary.

In Provincetown the crashing tide sent spray roof-high over buildings on MacMillan Wharf and nearby piers. Crews of fishing vessels were kept busy strengthening moorings.

In East Dennis, Bridge Street was washed out. It was repaired several hours later by highway crews. In Wellfleet, the heaviest water damage hit Mayo's Beach road . . .

. . . Water breaking over the boulevard seawall on Western avenue, Gloucester, drenched the area, and at Pavilion Beach, in the inner harbor, it climbed the back walls of a plant of the BirdsEye division of General Foods. The bridge leading into Annisquam was awash and cars were rerouted.

The water reached to within one foot of the windows of the Gloucester House on the Gloucester waterfront . . .

FIGURE 98.—A newspaper account of the dual east-west coast tidal flooding of 1959 December 29–30, as it was experienced in the vicinity of Boston, Mass.

highest tides in 108 years," are contained in the latter article.

The perigee-syzygy separation-interval at the time of this flooding was -18^h. The peak of the flood tides—indicated in the second of the immediately succeeding news articles as occurring in the vicinity of Cape Cod at 1100^h on December 29—closely followed the predicted high water for Boston (Commonwealth Pier) of 11.9 ft at 1016^h (e.s.t.) on this date. The corresponding predicted maximum range was 14.1 ft. For comparison, the tide level at mean high water springs is 10.3 ft, and the mean spring range is only 11.0 ft.

These rising perigean spring tides reached a slightly higher level of 12.0 ft at Boston at HHW (1109^h e.s.t.) on December 30 (as the result of the time lags introduced by phase age and parallax age), and then receded.

* * *

On the west coast, the tidal flooding produced was occasioned by the same condition of perigean spring tides that prevailed on the east coast, coupled with strong onshore winds. To show the basis for these winds, the synoptic weather map for 1959 December 30 would have to be used, since the coastal flooding on the west coast occurred on this date. However, on the 1959 December 29 map, a low-pressure trough is already seen to be moving from the south along the California coast, intruding between two high pressure cells—one off the coast and the other centered over northeastern Nevada and southern Idaho.

The strong winds produced over San Francisco Bay on December 30 resulted from the steepening pressure gradient associated with this low pressure system approaching the mid-California coast from off the Pacific. Since no strong winds are indicated at San Francisco on the weather map of December 29, those mentioned in the *Storm Data* report must have been of relatively short duration, with the principal flooding effects being due to the augmented perigean spring tide.

These tides reached their highest level of 6.9 ft at San Francisco (Golden Gate) on 1959 December 29 at 1023^h (P.s.t.). The maximum range for this date was 8.4 ft. The predicted higher high water at Golden Gate on December 30 at 1112^h (P.s.t.) was 6.7 ft, and the predicted maximum range on this date was 8.2 ft. The corresponding values of mean higher high water and diurnal range at Golden Gate are 5.4 ft and 5.7 ft.

Because the onshore wind movement was neither sustained for a long period over San Francisco Bay, nor of extreme intensity, the accompanying flooding damage from the perigean spring tides was not nearly as consequential here as in the vicinity of Boston.

From: *STORM DATA,* Vol. 1, No. 12, December 1959

I–83e,w—Coastal Flooding of: 1959 December 29–30, Maine, Massachusetts, New Hampshire; San Francisco Bay Area, California

MAINE

Coastal ------- "Dec. 29—Abnormally high tides flooded waterfront along entire coast. Major damage south of Rockland over area with eastward exposure to the sea. Coastal streets and highways were flooded. Water poured into cellars of homes and business establishments. Five summer cottages were demolished by the huge waves in the Biddeford area. Small craft were reported lost all along the coast. A number of roads were washed out. The tide also backed up the Kennebunk River, flooding Dock Square at Kennebunkport. Hundreds of lobster traps were wrecked or washed away.

MASSACHUSETTS

Coastal ----- "Dec. 29—Unusually high normal tides, strong to gale-force easterly winds, and a full moon, combined to produce the highest tides in at least 50 years, and possibly as much as 108 years. Central and northern portions of the coast bore the brunt of the tidal attack. Tidal flood waters engulfed all immediate coastal areas, and towering waves battered coastal installations and leaped seawalls. Water reached a depth of about 6 feet in the streets of Hull. At Nantasket Beach the waves tore out a 100 foot section of parking area pavement to a depth of 10 feet. Several thousand families were evacuated from their homes by the Coast Guard, Harbor Police, or Fire Departments. Thirty families were evacuated because of a flood-induced gas leak. Heavy stones and debris were hurled onto shore areas by the giant waves. Plows were used to clear the affected area. Lobstermen lost many traps. Small boats were washed away, and others were engulfed. Some beach areas were markedly eroded by the pounding surf. Flooded cellars crippled heating equipment in several thousand homes and caused heavy losses of inventory at business establishments. Many homes were badly damaged by flood and surf.

202-509 O - 78 - 27

NEW HAMPSHIRE

Coastal ----- "Dec. 29—Combination of spring tides and winds produced tide levels up to 14 feet above mean low water. Giant breakers smashed coastline. At Rye, wind-swept waters spilled over, damaging a seawall, flooding roads, and hurling shale piles to a depth of 3 feet across a half-mile stretch of highway. Lobstermen and fishermen counted heavy losses from the abnormally high tides and surf.

CALIFORNIA

San Francisco Bay Area. "Dec. 30—Strong winds combined with high tides to flood low-lying areas of the southern San Francisco Bay area. One man was drowned when his small boat capsized. A painter lost his life when he was blown from a scaffold at the sixth story of a Palo Alto building."

4. The Tidal Flooding of March 6–7, 1962

The great tidal flooding (Key No. J–85) which struck the entire coastline of the United States from South Carolina to Maine (with the principal damage being experienced between Long Island, N.Y., and Hatteras Outer Banks, N.C.) on March 6–7, 1962 is, without doubt, the most widespread nonhurricane-induced coastal flooding which has occurred along the North American eastern coastline during the entire period of coverage of this study, 1635–1976.

So thoroughly has this event been documented since its occurrence (cf., the reference source list opposite J–85 in table 1) that, with appropriate narrative excerpts included from *Climatological Data—National Summary* and *Storm Data,* it is additionally necessary only to assemble certain facts in résumé.

Of first importance is the consideration that, with the initial severe flooding occurring in the dark of the Moon and in the early morning hours of winter predawn, as well as under completely cloudy and snowswept skies, this catastrophe resulted in the loss of 40 lives and property damage estimated at 0.5 billion dollars. Incalculable loss was incurred as a consequence of coastal erosion.

Second in significance is the very near coincidence of this flooding event with a proxigee-syzygy alignment having a mean epoch of 1962 March 6 at 0430^h (e.s.t.), just 3.5 hours before the initial peak reached by the inflooding tides at Sandy Hook, N.J., (see fig. 111) and some 28 hours before the highest tidal peak reached on the following day. This latter flooding included the normal delay factor induced by phase age and parallax age at times of perigee-syzygy. The separation-interval between proxigee and syzygy in this occurrence was only —31 minutes. The parallax of the Moon at the mean epoch of proxigee-syzygy was 61′26.6″.

The third fact of significance is the manner in which reinforcement was given to the high tides already present at proxigee-syzygy by the merging of two atmospheric low pressure systems at a point midway along the east coast, followed by the easterly movement of the combined system offshore, and its subsequent blocking by a strong, nearly stationary high pressure system which had moved southward off the east coast of Canada.

The atmospheric pressures at the centers of both of the initially converging lows was 1,008 milibars. Although the central pressure of the combined low was only 992 mb as it left the coast, the cyclonic cell deepened and intensified after it left the coast. By 0100^h on March 7, the central pressure had dropped to 984 mb.

The process of successive buildup of this active wind-producing system is shown in the series of three accompanying surface synoptic weather maps for 1962 March 5, 6, and 7, each plotted for 0100^h (e.s.t.). (See figs. 99, 100, 101.)

On the March 5 map, an extratropical low pressure center with accompanying frontal wave is seen to be developing off the southeast coast of the United States, centered at about 30°N. latitude and 75°W. longitude. A second low pressure system is centered at the same time over southern Ohio. Falling pressures and the isallobaric gradient indicate its projected movement to be almost directly eastward.

The weather map of March 6 shows that the two low pressure systems, on a collision course, have merged, with the center of the combined system being located at a point some 100 nautical miles east of Chesapeake Bay. The pressure at the center of the new single low has deepened to 992 mb, and the winds have intensified strongly, with average easterly and northeasterly winds onshore from 32–37 mph (28–32 knots) at map time, increasing as the day goes by, including isolated peak gusts to 81 and 84 mph (70 and 73 knots).

The weather map for March 7 shows that the center of the low pressure system has moved only slowly east-southeastward to an offshore location centered at about 35°N. latitude and 70°W. longitude. Its forward motion has become blocked by a strong, near-stationary high pressure cell which has intruded southeastward from off the Canadian coast and which, while not appearing on this weather map of the United States and surrounding

TABLE 29.—*Surface Synoptic Weather Maps for Cases of Tidal Flooding Receiving Special Attention in the Text*

Key letter and serial No.	Weather map date and mean perigee-syzygy date			Perigee—syzygy (hours)	Location of tidal flooding
J–85	1962	March 5 March 6	1. 0h 4. 5h	(−31 *min.*)	Entire mid-Atlantic coast from Long Island, N.Y. to Outer Banks, N.C.
J–85	1962	March 6 March 6	1. 0h 4. 5h	(−31 *min.*)	Do.
J–85	1962	March 7 March 6	1. 0h 4. 5h	(−31 *min.*)	Do.
86	1962	October 12 October 13	1. 0h 3. 5h	(−9)	Local estuaries and bay locations, Oreg., Wash., and northern Calif.
N–99	1974	January 7 January 8	7. 0h 7. 0h	(−2)	Santa Barbara, Santa Monica, and San Clemente; Newport, Capistrano, and Malibu Beaches, Calif.
N–99	1974	January 8 January 8	7. 0h 7. 0h	(−2)	Do.
N–99	1974	January 9 January 8	7. 0h 7. 0h	(−2)	Do.
O–100	1976	March 16 March 16	7. 0h 6. 0h	(+16)	Beaches in Massachusetts, New Hampshire, and Maine, and northward to Halifax, Nova Scotia.

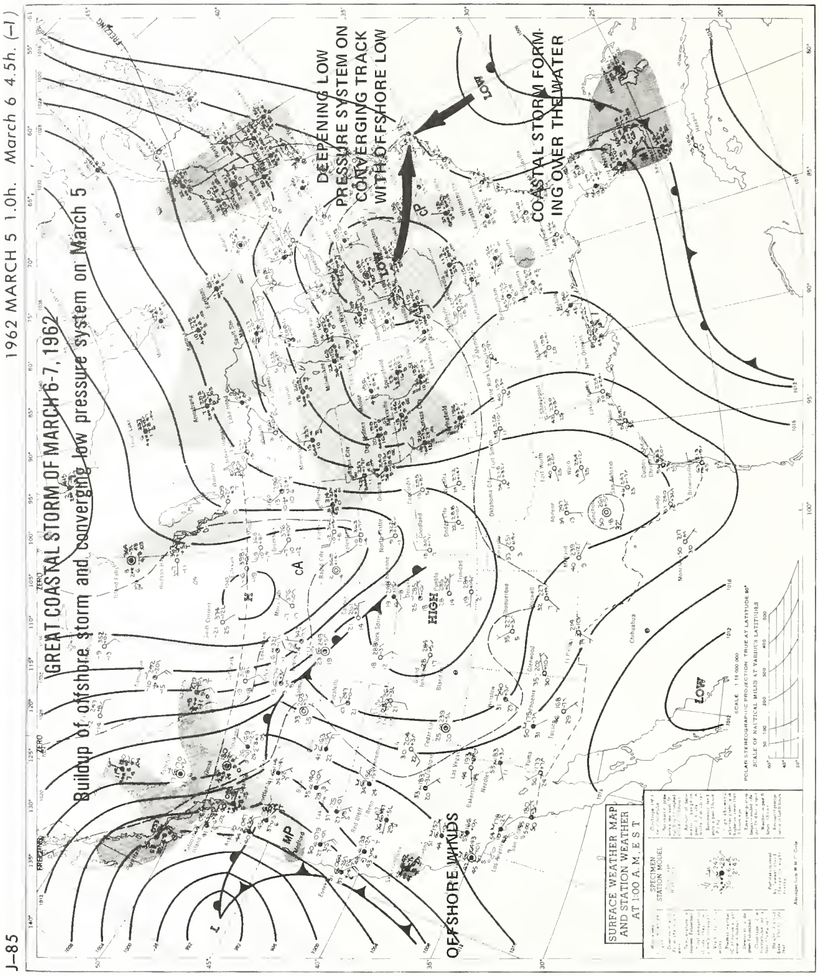
waters, lies over the Atlantic to the east of the blocked low. This low pressure cell has meanwhile expanded and elongated along a southwest-northeast axis. The resulting "fetch" of overwater surface wind movement directed, on the north side of the low, from the sea onto the land, has thus been extended to several hundreds of miles.

During the time that this offshore low pressure system had been deepening (979 mb being the lowest pressure actually recorded at sea) the barometric gradient had been steepening. Greatly strengthened, gusty winds resulted, blowing onshore from directions originally northeast over the North Carolina and Virginia coasts to final east and east-northeast components over the New England coastline. Because of the impaired movement of the low pressure center, these intensified winds continued with little diminishment, but with changing locations of maximum onshore intensity, along the coastline for some 65 hours, throughout five successive high tides. Although, as mentioned, peak gusts up to 84 mph (73 knots) were recorded, the average coastal onshore winds during the height of the storm ranged from about 21 to 49 mph (18 to 42 knots).

The devastating effects of the severe offshore storm, plus augmented proxigean spring tides, are illustrated in various forms among the accompanying graphic materials. Representative scenes of extensive inundation of the coastline, severe beachfront erosion, flooding of both suburban homesites and coastal industrial facilities, destruction and toppling of beach homes (and their transport to sea), and the complete demolition of waterfront condominiums, are shown in figs. 102–109. The frontispiece of the book also contains a very meaningful representation of the extent of damage that such severe tidal flooding can cause. The various contemporary newspaper accounts included in the present section and in table 5 provide valuable supporting information in connection with the 1962 catastrophe.

A technical analysis of the time-rate of buildup of this flooding event is also possible from a study of the accompanying graphs. Fig. 110 shows the progress of an accelerated rise in the coastal flooding waters resulting from proxigean spring tides plus onshore winds at Atlantic City, N.J., over a 5-day period bracketing the actual flooding event. The various sets of broken lines in this figure represent individual plots of *observed* (i.e., recorded) hourly heights surrounding the time of each day's higher high water in the period from March 5 to March 9. (Note that the vertical tidal height is plotted in meters as well as feet.) For comparison, the two solid curves indicate the *predicted,* or purely astronomically induced tide for March 6 and 7. In all cases, the appropriate curve is plotted for a 10-hour period in each day, centered on HHW.

The accelerated rates of growth of these storm tides, in excess of those which are astronomically induced, are obvious from the shifting of the observed curves to the left of the predicted curves along the time scale of each diagram. The considerably greater amplitudes of these observed curves, in consequence of the sustained wind action, and the resultant sharp peaks, rather than pre-



1962 MARCH 5 1.0h. March 6 4.5h. (–1)
J–85
GREAT COASTAL STORM OF MARCH 6-7, 1962
Buildup of offshore storm and converging low pressure system on March 5
DEEPENING LOW PRESSURE SYSTEM ON CONVERGING TRACK WITH OFFSHORE LOW
COASTAL STORM FORMING OVER THE WATER
OFFSHORE WINDS
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M. E S T

FIGURE 99.

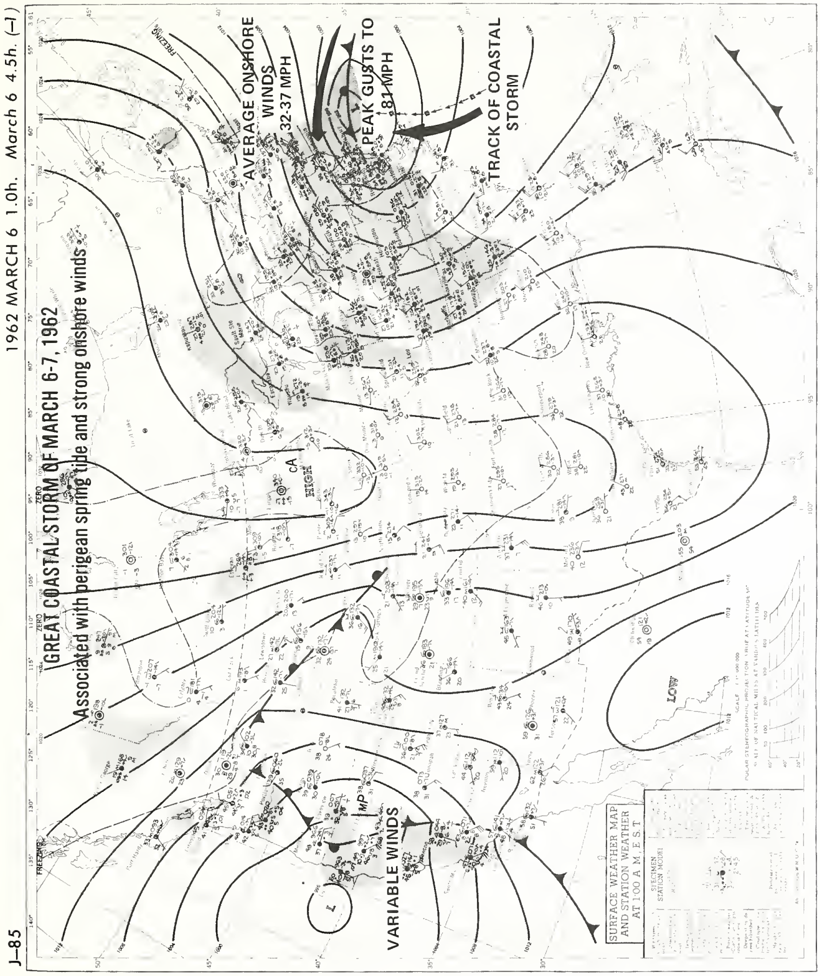

1962 MARCH 6 1.0h. March 6 4.5h. (–1)
J–85
GREAT COASTAL STORM OF MARCH 6-7, 1962
Associated with perigean spring tide and strong onshore winds
AVERAGE ONSHORE WINDS 32-37 MPH
PEAK GUSTS TO 81 MPH
TRACK OF COASTAL STORM
VARIABLE WINDS
HIGH
LOW
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.

FIGURE 100.

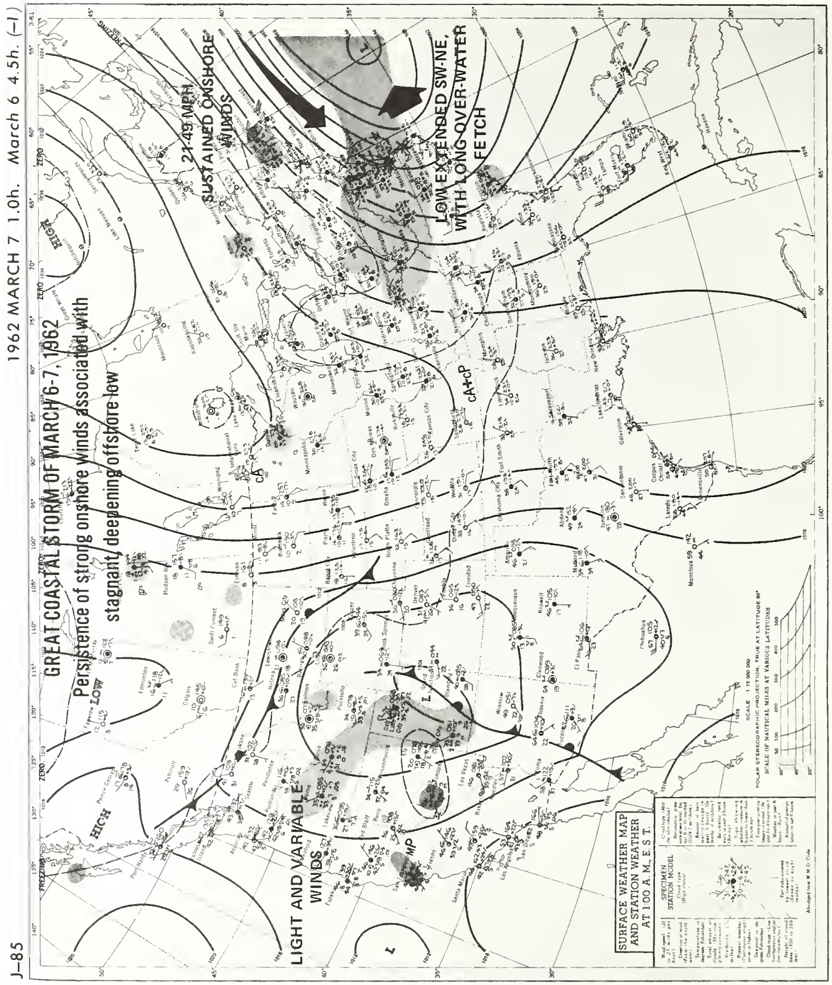

1962 MARCH 7 1.0h. March 6 4.5h. (–1)
J–85
GREAT COASTAL STORM OF MARCH 6-7, 1962
Persistence of strong onshore winds associated with stagnant, deepening offshore low
21-49 MPH SUSTAINED ONSHORE WINDS
LOW EXTENDED SW-NE, WITH LONG OVER-WATER FETCH
LIGHT AND VARIABLE WINDS
SURFACE WEATHER MAP AND STATION WEATHER AT 1:00 A.M., E.S.T.

FIGURE 101.

Courtesy of U.S. Army Corps of Engineers (Philadelphia District)

FIGURE 102.—The inundating effects of the great mid-Atlantic coastal storm and tidal flooding of 1962 March 6–7 upon the Grandview Beach section of the City of Hampton, Va. A very close perigee-syzygy alignment occurred on 1962 March 6.188 e.s.t.

Courtesy of U.S. Army Corps of Engineers (Philadelphia District)

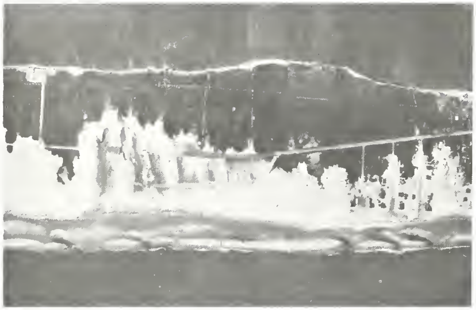
FIGURE 103.—Devastation caused by the wind-driven tidal assault of 1962 March 6–7 at Bethany Beach, Del. Note the completely toppled homes. This aerial photograph was taken on March 11.

Courtesy of U.S. Army Corps of Engineers (Philadelphia District)

FIGURE 104.—Beach homes at Rehobeth Beach, Del., knocked over and reduced to rubble by the impact of the 1962 March 6–7 tidal flooding.

Courtesy of U.S. Army Corps of Engineers (Philadelphia District)

FIGURE 105.—Nearly total demolition of the Atlantic Sands Resort Apartment at Rehobeth Beach, Del., by the 1962 March 6–7 tidal onslaught.



Source: U.S. Coast and Geodetic Survey (Aerial Photogrammetric Survey)

Figure 106.—Severe erosion of the shoreline along the south coast of Long Island, N.Y., caused by the tidal flooding incursion on 1962 March 6–7. The coastal highway was rendered impassable by huge, wave-transported mounds of sand.

Courtesy of U.S. Army Corps of Engineers (Norfolk District)

Figure 108.—Onshore encroachment of seawater at Norfolk, Va., associated with the 1962 March 6–7 tidal flooding. The area shown is on Moran Avenue between Princess Anne Road and Olney Road.

Source: U.S. Coast and Geodetic Survey (Aerial Photogrammetric Survey)

Figure 107.—Portion of barrier beach south of Mecox Bay, near Southampton, Long Island, N.Y., breached by the tidal flooding of 1962 March 6–7.

Courtesy of U.S. Army Corps of Engineers (Norfolk District)

Figure 109.—The Building 27 warehouse and pier at Fort Norfolk, Va., were extensively inundated by the 1962 March 6–7 coastal flooding event. Note the top of the submerged car in the middle distance.

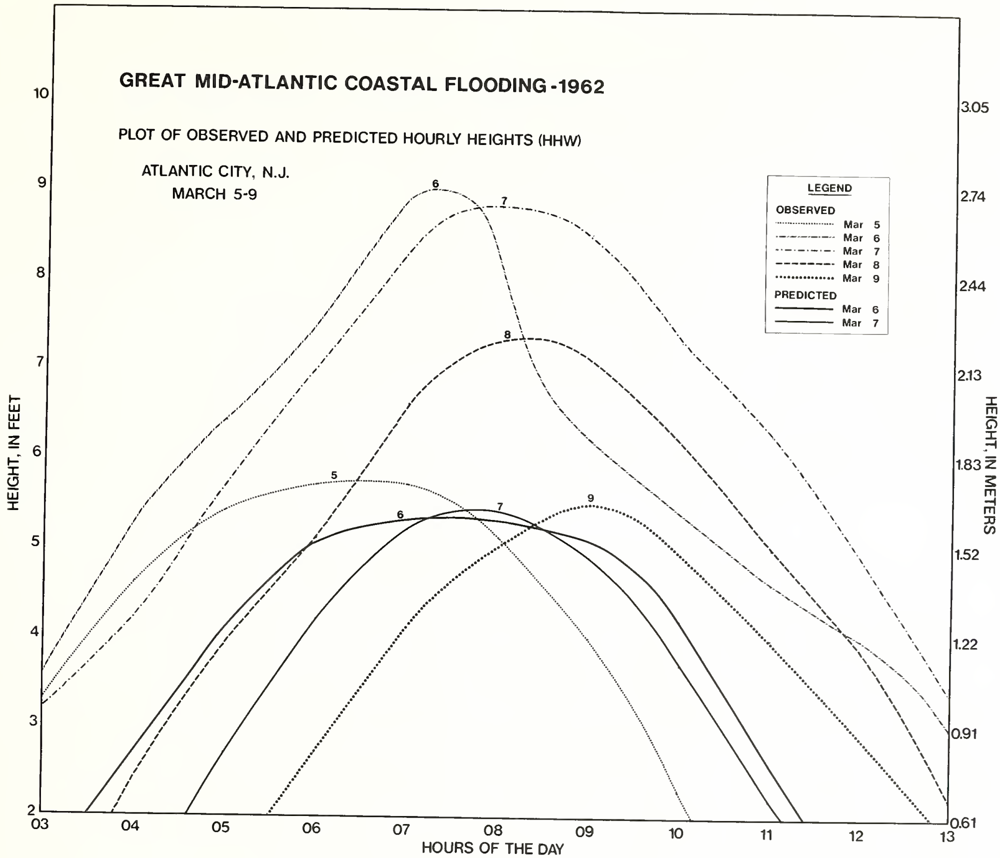


FIGURE 110.

dicted plateaus, of tidal maxima on March 6 and 7 also are clearly evident.

Fig. 111 illustrates the observed rapid buildup and less rapid subsidence of the higher high water phase of the tides at Sandy Hook, N.J., over 7 successive days from March 4 through March 10.

The considerable damage to the piers at Atlantic City caused by these repeated extreme rises in water level, and the hurling of ponderous masses of water against the piers by strong winds, is shown in fig. 113a.

Fig. 115a depicts tidal flooding of the streets in Norfolk, Va., during the earlier phase of the low pressure center's offshore movement when the surface winds at Norfolk were still directed onto the coast.

Appropriate newspaper accounts (figs. 112–115) as well as official analyses from *Climatological Data—National Summary* and *Storm Data* relative to the meteorological circumstances accompanying this coastal flooding are included on the following pages.

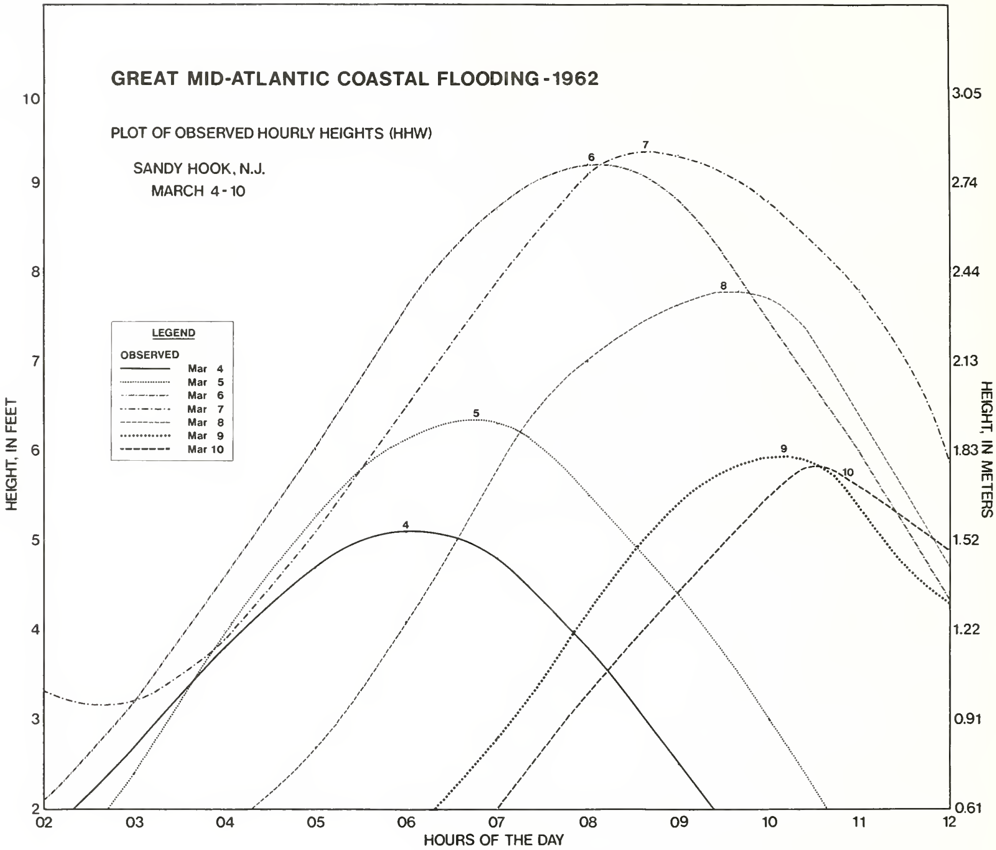


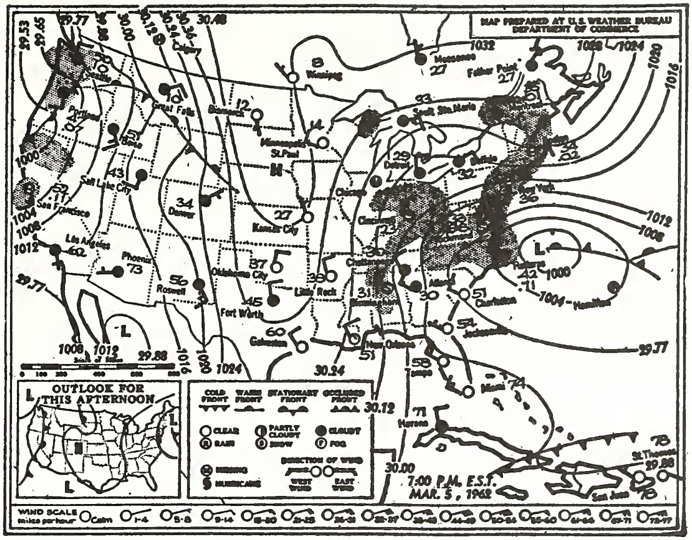
FIGURE 111.

Fig. 161a in chapter 8 further represents the predicted rate of tide rise at Breakwater Harbor, Del., as a function of the proxigean spring tide which—acted upon by supporting winds—precipitated this tidal flooding event. It is especially noteworthy that this method of analysis reveals the March 6.19 proxigee-syzygy alignment to lie centrally within a "window" of potential tidal flooding, with the peak of the tidal growth curve well into the potential danger zone.

To conclude the list of items under substantive review, it is, therefore, also significant for the future in connection with such tidal floodings to note that this circumstance was in no way predicted. (See the "Today's Forecast" and "Five-Day Forecast" columns from the *New York Times* in fig. 112.) Despite the very close proxigee-syzygy alignment (−31 minutes) accompanying this event, and the considerable potential for tidal flooding, the event was later described in all public announcements only as being associated with "spring" tides.

With the appropriate use of the data contained in table 34, the computer printout of table 16, and the developmental predictor equation of chapter 8, such a serious tidal flooding eventuality, it is to be hoped, can in the future be avoided.

The New York Times
Tues., March 6, 1962
Page 70 L+, Cols. 2–5



The Summary

Snow fell yesterday from the North Atlantic States to the Mississippi Valley and in the higher parts of the Pacific States. Rain fell in the North Atlantic States and the Pacific States.

Low pressure will dominate the East and the Pacific Northwest today. High pressure will extend from the Mississippi Valley to the plateau region.

Snow is the forecast today for the northern plateau region. Snow mixed with rain will fall from the North Atlantic States to the Appalachians. Rain will fall in the western plateau region and the Pacific States. It will be colder in the Atlantic States, the Ohio and Mississippi Valleys and the lake region.

Today's Forecast
United States Weather Bureau
(As of 11 P. M.)

NEW YORK CITY, NEW JERSEY, LONG ISLAND, LONG ISLAND SOUND, ROCKLAND AND WESTCHESTER COUNTIES, SOUTHEASTERN NEW YORK, EASTERN PENNSYLVANIA AND CONNECTICUT—Snow today and tonight, highest temperature today in the 30's, northeasterly winds 35 to 45 miles an hour; lowest temperature tonight near 30. Cloudy and cold tomorrow.

(As of 5 P. M.)

MASSACHUSETTS, VERMONT, NEW HAMPSHIRE AND NORTHEASTERN NEW YORK—Snow, except snow or rain southeast portion today; snow north portion, snow or rain southwest portion tonight.

Day's Records
NEW YORK
Eastern Standard Time

	Temp.	Hum.	Wind (M.P.H.)	Bar.
Midnight	30	53	N 8	30.05
1 A.M.	30	56	N 6	30.04
2 A.M.	30	55	N 5	30.04
3 A.M.	30	56	N 6	30.02
4 A.M.	30	56	N 6	30.02
5 A.M.	30	56	N 5	30.03
6 A.M.	30	63	N 8	30.04
7 A.M.	31	61	N 8	30.05
8 A.M.	31	63	N 6	30.06
9 A.M.	32	66	NE 9	30.05
10 A.M.	35	67	NE 11	30.06
11 A.M.	36	69	NE 11	30.05
Noon	36	72	NE 13	30.04
1 P.M.	36	79	NE 15	30.00
2 P.M.	37	79	NE 16	29.98
3 P.M.	38	79	NE 17	29.95
4 P.M.	37	85	NE 16	29.93
5 P.M.	38	82	NE 16	29.98
6 P.M.	39	79	NE 17	29.98
7 P.M.	38	78	NE 18	29.98
8 P.M.	36	85	NE 19	29.93
9 P.M.	36	85	NE 21	29.93
10 P.M.	36	85	NE 23	29.91
11 P.M.	34	92	NE 25	29.86
Midnight	35	89	NE 27	29.82
1 A.M.	35	89	NE 27	29.81

Figure beside Station Circle indicates current temperature (Fahrenheit); a decimal number beneath temperature indicates precipitation in inches during the six hours prior to time shown on map.

Cold front: a boundary line between cold air and a mass of warmer air, under which the colder air pushes like a wedge, usually advancing southward and eastward.

Warm front: a boundary between warm air and a retreating wedge of colder air over which the warm air is forced as it advances, usually northward and eastward.

Stationary front: an air mass boundary which shows little or no movement.

Occluded front: a line along which warm air has been lifted from the earth's surface by the action of the opposing wedges of cold air. This lifting of the warm air often causes precipitation along the front.

Shading on the above map indicates areas of precipitation during the six hours prior to time shown.

Isobars (solid black lines) are lines of equal barometric pressure and form patterns which control air flow. Labels in millibars and inches.

Winds are counter-clockwise toward the center of low-pressure systems, and clockwise and outward from high-pressure areas.

Pressure systems usually move eastward at an average movement of 500 miles a day in summer and at a rate of 700 miles a day in the winter.

Five-Day Forecast
(March 6 through March 10)

SOUTHEASTERN NEW YORK, EASTERN PENNSYLVANIA, NEW JERSEY AND CONNECTICUT — Temperatures will average near normal, except 2 to 4 degrees below normal in extreme southern sections. It will be cold today and tomorrow with warming toward the end of the period. (Some normal high and low temperatures are: Albany 39-21, Atlantic City 46-33, Hartford 44-24, New York 46-31, Philadelphia 49-33 and Scranton 42-25.) Snow inland and snow or rain along the coast today and rain Friday or Saturday may total more than one-half an inch melted.

1962 Mar. 6
4.5h e.s.t. (−31 min.)

J–85

FIGURE 112.

The New York Times Wed., March 7, 1962 Page 24 L+, Cols. 1–4 (Continued from Table 5)

Snow, Rain, Gales, Tides Lash Mid-Atlantic States

(Continued from Page 1, Col. 3)

. . . The northeast storm developed with multiple centers, according to the Weather Bureau, including one low pressure area in Virginia and another southwest of Bermuda. It stalled in the face of a cold, high-pressure area from Canada . . .

. . . Twenty-three persons in Far Rockaway and six in Breezy Point were evacuated when high tides threatened their homes . . .

. . . Ferry service between Staten Island and Sixty-ninth Street, Brooklyn, was halted from 8:15 A. M. until 10:26 A. M. because high tides made loading of vehicles and passengers impossible . . .

. . . The Brooklyn-St. George ferry ceased operations again during high tide last night, starting at 7:30 o'clock . . .

. . . Flooding forced scores of families from homes in south shore communities.

Sections of Franklin D. Roosevelt Drive, the Belt Parkway in Brooklyn and the Hutchinson River Parkway in the Bronx were flooded and closed to traffic part of the day . . .

. . . High tides in the morning and evening halted service on the railroad between Island Park and Long Beach . . .

. . . The Erie-Lackawanna ferry to Barclay Street was closed from 7:25 to 10:30 A. M., and again during evening high tide, starting at 6:55 . . .

. . . The Jersey Central Railroad ferry from Jersey City to Liberty Street was halted from 7 to 10:15 A. M. Flooding later halted the line at Jersey City and Bayway, so that until noon, service ended at Bayonne. Jersey Central normally handles 10,000 passengers each morning.

Ferry service was also suspended by the Jersey Central last night during high tide . . .

. . . Flooding in the Atlantic resort area and neighboring communities was extensive. A fifty-foot section at the end of the Steel Pier, used for a water circus, was washed away, and a thirty-foot section in the midway portion of the pier was demolished. So was a 200-foot section of the boardwalk in the Inlet section while a sixty-five-foot boardwalk approach there was washed across Maine Avenue . . .

. . . The staff of The Atlantic City Press, a morning newspaper, worked with its composing room and much of its editorial office covered by water at high tide . . .

. . . Municipal offices in Asbury Park's Convention Hall were flooded. Several hundred feet of the boardwalk were damaged as tide-driven sand made the structure bulge upward.

The Loveland Town bridge over the Inland Waterway Canal in Point Pleasant between the Manasquan River and Barnegat Bay collapsed when racing waters undermined its pillars.

Almost every house in Sea Isle City, N. J., which has 1,200 residents, was reported flooded by four to five feet of water.

Seventy-five families were evacuated from Island Park, Oceanside, Bellmore and Seaford, L. I., when water rose two to three feet. Wind-driven waves twenty feet high stormed Fire Island, carrying away sand dunes on the ocean side and wrecking some Boardwalk and other facilities . . .

. . . The barrier beaches of Long Island, from Coney Island to Montauk Point, were battered heavily. Many streets in Coney Island were covered by up to two feet of water last night.

In Nassau County, flooding cut off sections of Merrick, Baldwin Harbor, East Rockaway and Point Lookout.

High seas took a heavy toll of the dunes from Fire Island to Montauk. At Westhampton Beach, three luxurious summer homes were demolished . . .

. . . In Fairfield County, Conn., several families were evacuated in shore homes in Norwalk, Darien and Westport . . .

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4.5h e.s.t. (– 31 min.)

J–85

FIGURE 113. Source: U.S. Coast and Geodetic Survey (Aerial Photogrammetric Survey)

FIGURE 113a.—Aerial photograph taken over Atlantic City, N.J. at 1030 e.s.t. on March 25, 1962, showing damage to Steel Pier by severe tidal flooding of March 6–7. Flight altitude, 10,000 ft; scale 1:20,000.

The New York Times Thurs., March 8, 1962 Page 1, Cols. 6, 7 (Late City Ed.)

Storm Hits Coast 2d Day; 27 Dead, Damage Heavy

By Russell Porter

The heavy storm that swept the mid-Atlantic states Tuesday struck again yesterday with high tides and winds along the coast. At least twenty-seven persons were reported dead in its wake as the storm swept out to sea.

Thousands of homes were wrecked or damaged from Virginia to New England, and thousands of persons were evacuated. Hundreds were marooned without electricity, gas or drinking water, and food ran low. Rescuers used trucks, cars, boats, amphibious vehicles and helicopters . . .

. . . The Weather Bureau predicted that strong, gusty winds and above-normal tides would continue through the night, but that the wind and water would subside today.

Tidal waters in this area were expected to rise three to five feet above normal during the night, and two to three feet higher than usual in the early morning. There may be more flooding . . .

. . . The New York metropolitan area was hit hard yesterday by extremely high tides, heavy surf, violent winds, flooding and power failures. Ferry, rail and highway traffic was disrupted.

Winds up to fifty miles an hour blew across the city. Streets in lower Manhattan, and sections of the East River Drive, the Hutchinson River parkway and the Belt parkway were closed by flooding. Coney Island was flooded and hotels and apartment houses in the Rockaways were evacuated . . .

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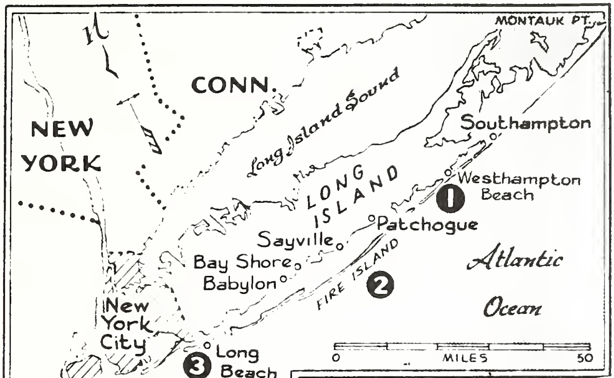
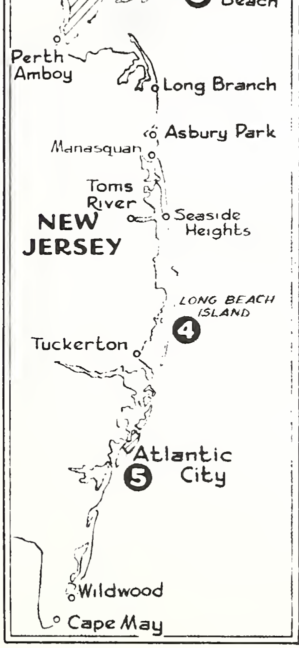
The New York Times
Thurs., March 8, 1962
Page 22 L++, Cols. 3–8

. . . Cape May, Monmouth and Ocean Counties declared states-of-emergency. All 700 residents of Long Beach Island were evacuated, and nine houses were seen floating in Barnegat Bay . . .

. . . State officials in Trenton last night estimated the damage in coastal areas at $30,000,000. Winds as high as forty miles an hour and abnormally high tides were still battering the coast.

At 7 o'clock last night the ocean broke through Long Beach Island, cutting off Beach Haven.

Police Chief Jerry Sullivan of Atlantic City predicted the damage would be "much more" than the $5,000,000 damage the city sustained in a hurricane in 1944. The resort city was swept by tides six feet high and winds that hit eighty-four miles an hour in gusts . . .

The New York Times **March 8, 1962**

HAVOC: Storm swept houses at (1) and (2) into ocean, inundated Rockaway area (3), routed Long Beach Island residents (4), and pounded Atlantic City (5).

. . On Long Island, Suffolk County Executive H. Lee Dennison also said damage was in the hurricane class. He asked Governor Rockefeller to declare the South Shore, along the Atlantic, a disaster area.

Mr. Dennison declared a state of emergency along the shorefront. He estimated property damage at more than $2,000,000.

More than seventy houses, including thirty-five on Fire Island, were destroyed on the barrier beaches of the county. Fifteen summer houses on the dunes at Westhampton Beach were undermined and swept out to sea. About twenty other houses were lost in near-by coastal resorts . . .

. . . Most ferries stopped running as the morning rush hour started, because of high tidal waters, heavy winds and power failures . . .

. . . The rising tide forced the suspension of ferry service between Staten Island and Manhattan between 8:05 and 9:18 P. M. Two boats with about 2,000 passengers

FIGURE 114.

NEW YORK (Cont.)

each stood off St. George, S. I., unable to dock because of high water . . .

. . . Service on the Tubes was suspended again last night when high tides flooded the tracks between Newark and Jersey City. The rising waters also forced cancellation of the Erie-Lackawanna ferry service between Hoboken and Manhattan at 8:50 P. M.

The Greenwood Lake and Newark lines of the Erie-Lackawanna Railroad were put out of commission by flooding. The Pennsylvania Railroad reported some commuter trains from North Jersey shore points delayed by high water, some as much as thirty minutes . . .

. . . Power on the Long Beach line of the Long Island Rail Road was cut at 8:25 A. M. for the third time in two days as third rails were flooded . . .

. . . Service was resumed at 1 P. M. but was interrupted again last night by the rising tide. It was expected to go back to normal when the tide receded.

Much of the East River Drive was closed. At noon a foot of water covered the roadway between Eightieth and Ninetieth Streets . . .

. . . The eastbound lane of the Belt was closed because of high tides at 9 P. M. over a three-mile section from Fort Hamilton Parkway to Bay Parkway. The westbound lane was closed at 10:30 and the police said the road would be reopened after the tides diminished.

Some streets in downtown Manhattan were also closed by flooding, including Pearl Street from John Street to Maiden Lane. The east side of Whitehall Street from the tip of Manhattan island to Front Street was under water.

The worst of the flooding in the city was in the Rockaways and near-by sections. Water covered the tops of parked automobiles in some areas.

Water from Jamaica Bay was so deep at Howard Beach that commuters were unable to wade through it to the subway and buses were unable to get to Hamilton Beach. About 100 marooned families were evacuated from Breezy Point at the west end of the Rockaway peninsula . . .

. . . Flood waters inundated Wallops Island, Va., a launching site of the National Aeronautics and Space Administration.

In Chincoteague, Va., 1,000 residents were evacuated after their homes began to break up under the pounding of the surf. At least five persons lost their lives there . . .

TIDE CYCLE AND WIND BLAMED IN FLOODING

WASHINGTON, March 7 (AP)—Winds from one of the worst winter Atlantic storms ever recorded, at a time of normally high tides, combined to produce the devasting high water today on much of the East coast.

The main path of the wind, out of the northeast, was along a line extending from about 300 miles off Cape Cod to the Virginia-North Carolina coast. In a meteorologist's or sailor's term, this is a long fetch of about 600 miles. Such a long fetch gives time and opportunity for the winds to pile up water before them. The rush of wind, pushing and dragging water, came at a time when tides in the normal course would have been high.

In the twenty-eight-day moon cycle there is a period when the gravitational forces of the moon and the sun, acting on the oceans, pull in opposite directions, diminishing the tides. There is another period when these forces pull together and give higher tides. This storm happened to come in such a period . . .

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4.5h e.s.t. (−31 min.) **J–85**

FIGURE 115a.

Courtesy of U.S. Army Corps of Engineers (Norfolk District)

FIGURE 115a.—The corner of Bank Street and City Hall Avenue in downtown Norfolk, Va., showing the tidewaters receding after the great mid-Atlantic coastal flooding of March 6–7, 1962. Note the dark 3-foot highwater mark on the wall at the right.

Abstracted from: Cooperman A. I., and Rosendal, H. E., "Great Atlantic Coast Storm, 1962, March 5–9," U.S. Weather Bureau *Climatological Data—National Summary,* vol. III. 1962, p. 137.

"A slow moving late winter coastal storm combined with spring tides (maximum range) wrought tremendous destruction to coastal installations from southern New England to Florida on March 6–9. This storm, which consisted of a series of LOWS, has been described as one of the most damaging extratropical cyclones to hit the United States coastline. Although gale-force winds, and at times hurricane-force winds, accompanied the storm, this is not unusual for a North Atlantic winter extratropical cyclone. It was the long fetch and the persistence of these strong northeasterly winds which raised the spring tides to near record levels. The tidal flooding which attended this storm was in many ways more disastrous than that which accompanies hurricanes. The storm surge in tropical cyclones generally recedes rapidly after one or two high tides, but the surge accompanying this storm occurred in many locations on four or five successive high tides. In addition, many places reported runup of waves 20 to 30 ft high.

"This successive onslaught of wave and tidal action for over two days weakened and undermined even the more permanent shoreline structures, and after a period of time some suffered structural damage and collapsed. . . .

"The erosive effect of wave and tidal action changed the face of the immediate coastline, and on many of the well-known beaches the most severe loss was often the sand of the beach itself. In addition many new channels and inlets were cut in the shoreline. . . .

"Preliminary estimates of damage total about $200 million; 1,893 dwellings were destroyed, 2,189 sustained major damage, and 14,593 minor damage. Thirty-three persons are known dead; 340 received major injuries and 912 minor injuries.

". . . This storm, although it first appeared as a wave on the polar front on the 4th off the Florida coast, did not deepen to any extent until it reached the Hatteras area. . . .

"When the coastal storm started to form as a wave on the polar front off the Atlantic coast of Florida on the 4th, the dominating features on the weather map were a strong blocking HIGH centered over the Canadian Arctic Archipelago with a ridge extending south-southeastward over the Middle Atlantic States and a moderate LOW located over the upper Mississippi Valley. On the 5th the interior LOW with a very deep circulation aloft moved along the southern fringes of the Canadian HIGH to the Ohio Valley, where the surface LOW began to dissipate. In the meantime, a wide area of low pressure with several separate centers had developed between the Carolina coast and the wave off the Florida coast. The deep LOW aloft which was associated with the dissipating interior LOW continued its eastward movement, and by the 6th it was located over the Carolina coast. This triggered the intensification of the coastal LOW which still consisted of several ill-defined centers. The usual northeastward movement of such a system was retarded by the presence of the blocking HIGH which was now centered near Labrador. On the 7th and 8th this HIGH continued to move southward toward northern New England, as the intensifying coastal storm started to drift east-northeastward. This resulted in the LOW elongating in a roughly east-west direction with a very steep pressure gradient. . . . A long fetch of northeasterly winds was set up by the configuration of this elongated LOW. This pattern persisted from late on the 6th to the 8th, and the resulting strong northeasterly winds piled up additional water on top of the high spring tides and created mountainous seas which pounded savagely at the coastline.

". . . [A sea-condition analysis revealed] a significant wave height of more than 40 ft at 0000 G.m.t. of the 8th. The cause of such high seas from the east . . . was the slow movement of the system and its elongated shape. Furthermore, the westward traveling seas were already set up, by the previous LOW, across the entire ocean to Europe, . . . [facilitating the breakdown of the] . . . easterly winds and rebuilding of waves traveling in the opposite direction.

"The pressure gradient near the center of the system was not very steep, and the lowest pressure recorded was only about 979 mb which is deep for an extratropical LOW in the western North Atlantic, but not too unusual. Within this "shallow" and fairly large region of the lowest pressures, two or three separate low pressure cells could be detected during the first few days of the storm by analyzing the wind and pressure data received from ships in the area. These cells appeared to rotate within the primary system with the forward one weakening and a cell toward the rear generating and taking over. This caused the movement of the system as a whole to be rather erratic, and at times the storm appeared to move backward or loop. Any single track is thus difficult to construct.

"Precipitation was heavy over the Middle Atlantic Coast with interior portions of Virginia and Maryland receiving up to three feet of snow accompanied by some thunderstorm activitiy during the development stage of the storm. As the LOW became more mature, only light precipitation fell to the north of it, and in New England the storm was known as a "dry northeaster." Much of the driving energy was probably caused by the transformation of potential energy stored in the large warm HIGH into kinetic energy along the steep pressure gradient of this LOW. . . .

"NEW ENGLAND.—Central and northern New England escaped relatively lightly the effects of the coastal storm. Seas came crashing over walls along all parts of the coast south of Portland, Maine. Low lying coastal highways were flooded and closed to traffic as tides ran up to 5 ft above normal. Damage to seawalls was slight along the Maine coast but was heavier along the New Hampshire shore. Complete sections of old seawalls were washed out at the New Hampshire resort towns of Rye, North Hampton, and Hampton. Some structural damage to waterfront installations, mostly of minor nature, occurred in New Hampshire and Massachusetts, and many cellars in low-lying districts were flooded. Most damage in Connecticut and Rhode Island was confined to beaches along the south coast and Block Island. There was some flooding in low susceptible places in Bridgeport, East Haven, and Greenwich, and the Quinnipiac River overflowed in North Haven doing some damage. An oyster boat and barge were sunk near New Haven. The highest winds reported on the East Coast occurred at Block Island. The Weather Bureau Airport Station recorded a peak gust of 84 mph and a sustained wind of 76 mph on the morning of the 6th.

"Preliminary damage figures for the New England States: Maine, $25,000; New Hampshire, $27,000; Massachusetts, $250,000; Rhode Island and Connecticut, $1 million. No lives were reported lost in the New England area.

"NEW YORK.—The strong winds pushed the ocean waters onshore, producing severe flooding. At the time of high tides on the 6th and part of the 7th, the waters reached between 4 ft above mean sea level along the western end of Long Island and 7 ft above in New York Harbor. On top of the high water the storm sent huge waves, estimated at 20 ft high in places, to break against beachfront installations. Damage was greatest on the south shores of Richmond, Brooklyn, and Queens Boroughs in New York City, and along the barrier beaches of Nassau and Suffolk County, eastward to Montauk Point. On Long Island's South Shore about 100 houses were swept into the sea, 35 of them on Fire Island alone. Numerous other buildings suffered water damage, and cellars, streets, and highways in waterside areas were flooded. There was also wind damage to utility lines, trees, signs, and windows, but these losses were comparatively minor.

"Preliminary and unofficial damage estimates are in the $10–$15 million range. Fortunately, no loss of life or injuries were directly attributable to the storm, although many families were forced to evacuate threatened dwellings.

"NEW JERSEY.— . . . The major damage was restricted to property facing the beach itself. The entire coastline and even the Delaware Bay area suffered from the high tides. Highways along the coast were cut in many places or buried under several feet of sand. Thousands of homes along the coast were damaged or destroyed. One of the hardest hit areas was Long Beach Island. At Atlantic City the major damage was the cutting of the famed Steel Pier. The storm swept away the quarter-mile section of the pier which connects the auditorium at the end of the pier with the mainland boardwalk. . . .

"The storm did an estimated $80 million damage in New Jersey. Deaths mounted to 14 with 12 other persons, including nine aboard two fishing trawlers, missing and presumed dead.

"DELAWARE AND MARYLAND.—The Atlantic coast resort towns bore the brunt of the storm in these States. Four or five consecutive high tides with 20–30-ft waves right against the coast caused serious beach erosion and destruction of shoreline property along the Delmarva Peninsula from Cape Henlopen and Cape Charles. At Rehoboth Beach, Del., and Ocean City, Md., complete destruction to severe damage was inflicted to many resorts on the immediate coast while tidal flooding occurred farther inland. Tides at Ocean City were estimated to be 5 to 6 ft above normal. . . . The boardwalks were reduced to splinters early in the storm, . . . and in . . . resort areas much of the sand was washed away. . . . Less serious flooding occurred in the Bay areas. The rain-soaked soil of late winter probably prevented severe damage to inundated farmlands farther inland or in the Bay areas. It is estimated that from 1.2 to 1.5 million broiler chickens and an unknown number of incubator eggs were lost chiefly due to power failures in the Delmarva production area.

"Preliminary estimates on damage for the Delaware-Maryland shore are about $50 million. Seven deaths were reported in Delaware and three in Maryland.

"VIRGINIA.—The intense coastal storm brought as severe damage to the Atlantic coastline of Virginia as any extratropical storm in modern times. The resort areas near Virginia Beach in particular had heavy property losses. Many hundreds of homes on the beaches were totally destroyed and thousands were damaged. The fishing pier at Virginia Beach was destroyed. The largest pile driver in the world, a $1½ million machine, was turned over on its side in deep water. One of the communities hardest hit along the Virginia section of the Delmarva Peninsula was Chincoteague Island. Extensive damage was done to the fishing boats and nets, homes and livestock. . . . Many ponies on Chincoteague drowned. More than 1,000 persons were airlifted by helicopter to the mainland during the storm. The NASA installation on Wallops Island also suffered considerable damage. High tides inundated large areas inside the Bay, and sections of Hampton Roads were under several feet of water. The 8.9 ft tide above mean low water, 5.6 ft above normal, was the highest tide caused by an extratropical cyclone and the third highest of record. More than 1,000 automobiles were flooded in the metropolitan area alone. The Chesapeake Lightship of the Coast Guard while on station at 36°59′N., 75°42′ W., or 17 mi east of Cape Henry Lighthouse was damaged by a 50-ft wave early on the 7th and forced to leave the station. At this time sustained winds were above hurricane force.

"Damage in Virginia is estimated at $30 million; however, the full extent is not known. In the city of Virginia Beach alone, damage amounted to about $16 million. Five deaths were reported in Virginia.

"NORTH CAROLINA.—The most destructive effects of the storm took place on Hatteras Island and northward. On the entire stretch to the Virginia line, a large percentage of the protective sand dunes along the ocean side of the elongated islands which constitute the Outer Banks were washed flat. A 200-ft wide inlet was cut, by waves and strong currents at the change of the tides, across Hatteras Island about 2 mi north of Buxton. The highway along the shore was destroyed or undermined in many places or covered with sand up to several feet deep. Many cars were stranded with only the rooftops appearing above the sand. Most of the damage to private property occurred in the Kill Devil Hills–Kitty Hawk–Nags Head area north of Oregon Inlet where many motels and summer homes suffered.

"Preliminary damage figures are estimated at $12 million which does not include the devastation to the land itself. Two deaths were reported in North Carolina.

"SOUTH CAROLINA.—Damage from the coastal storm in this State was mainly limited to tidal flooding and some beach erosion. A few cottages along the beaches were destroyed and others damaged. All beaches along the coast suffered in varying degrees from loss of sand in certain sections. Folly Beach is estimated to have lost 100 to 200 ft in width for one-quarter mile in an uninhabited area near the east end. . . ."

From: *Storm Data*, Vol. 4, No. 3, March 1962

J-86—Coastal Flooding of: 1962 March 6–7, East Coast of U.S., Maine–South Carolina

MAINE

Coastal South of Portland.	"Mar. 6–8—This area received fringe effects of a vast ocean storm that wreaked havoc along coastal areas farther south. Flooding of coastal lowlands and some road washouts were reported. Slight damage was reported to seawalls.

NEW HAMPSHIRE

Coastal -------	"Mar. 6–8—This area received fringe effects of a vast ocean storm that wreaked havoc to coastal areas farther south. A combination of wind-driven tidal surges and spring tides brought seas crashing over and damaging walls erected against them. Coastal lowlands were flooded and some road washouts were reported. Foundation of a beach-front home was washed out.

MASSACHUSETTS

Coastal Areas---	"Mar. 6–8—This area was relatively lightly affected by the vast ocean storm that wreaked havoc over coastal areas to the south. A combination of wind-driven tidal surges and spring tides brought seas crashing over and damaging walls erected against them. Complete sections of some old seawalls were washed out. Low-lying areas were flooded. Some structural damage to waterfront installations occurred and many cellars were flooded. About 100 residents of Kenberma Park, Hull, Mass., were evacuated as a precautionary measure. Winds reached and maintained gale force for long periods on the 6th and 7th. However, wind damage was scattered and mostly light and was generally limited to broken windows and downed signs. Many flights out of Logan Airport, E. Boston, were cancelled because of the winds there and the weather at other airports along the coast. A boy was injured when struck by a wind-blown storm door.

RHODE ISLAND

Coastal Sections.	"Mar. 6–7—Four successive high tides, 2–4 feet above normal, with gale-force winds and gusts to 80 mph in southern sections of the mainland and hurricane winds with gusts to 85 mph on Block Island, combined with surging waves to batter seawalls and destroy beaches as a great storm moved eastward in the Atlantic well south of Rhode Island. Strongest winds occurred on March 6, and highest tides on the morning of March 7. Considerable flooding in Newport, South Kingston, Bristol, Barrington and Warren. Many piers and boats damaged. Heavy waterfront sand erosion and some property damage with 3–5 feet of sand being stripped from beaches between Point Judith and the Pawcatuck River.

CONNECTICUT

Shore Areas----	"Mar. 6–7—Four successive high tides, 2–4 feet above normal, with gale-force winds battered seawalls as a major storm moved eastward in the Atlantic well south of the State. Greatest damage due to tidal flooding in Fairfield and eastern New London Counties with minor damage along rest of Coast. Sand erosion moderate along easternmost beaches. Wind damage confined to tree branches and downed powerlines.

NEW YORK

Coastal sections extending from the New York City area throughout Long Island and Montauk Pt.	"Mar. 6–8—A great Atlantic storm was centered off the Maryland-Delaware coast during the period. The extensive intensifying storm finally encompassed much of the North Atlantic and caused destructive winds, tides, and waves over much of the Atlantic seaboard from southern New England to Florida. The gale- to hurricane-force northeast winds from this great storm pushed the ocean waters onshore during at least five successive high tides in an unprecedented manner. On top of the near-record tides was repeated wave action of heights between 20 and 30 feet. Great and unprecedented damage was done to barrier dunes, beaches, and all types of shore installations. Damage was greatest on the south shores of Richmond, Kings, and Queens Boroughs in New York City, along the barrier beaches of Nassau and Suffolk counties, eastward to Montauk Point. One hundred or more houses were

swept into the sea. Many hundreds of buildings suffered water and structural damages. Streets and highways, utility lines and boats were severely damaged or wiped out. Much of the area lost its barrier dunes and beaches and left further inland properties exposed to future storms. Property damage expected to be well up in [the range from $5 million to $50 million.]

NEW JERSEY

Entire coastline of State, including Delaware and Raritan Bay.	"Mar. 6–8—A severe coastal storm, moving very slowly, combined with high tides on five consecutive occasions in a three-day period, wrought tremendous destruction to coastal installations. Hundreds of summer homes were demolished. The sand from beaches was washed away, changing the shoreline in many areas. Many new channels and inlets were cut in the shoreline. Highways were cut in many places, or buried under several feet of sand. A Navy destroyer, the MONSSEN, was beached about a half mile north of Beach Haven after breaking its tow. The destroyer was unmanned and was being towed to Philadelphia from Bayonne Navy Yard. Loss of life from the storm includes 6 persons missing and presumed dead. Five of those six were aboard a fishing trawler off the New Jersey coast. Agricultural losses were chiefly due to flooding of around 1,000 acres of Cumberland County, on Delaware Bay.

DELAWARE

Coastal Areas___	"Mar. 5–8—The storm deepened and nearly stagnated off the Virginia Capes giving sustained northeasterly winds for over 24 hours. The highest windspeed at Delaware Breakwater was NE 72 mph at 9PM on the 5th. The storm tide piled on top of the high spring tides to make the water up to 5 feet above normal. In addition, 20 to 30 foot waves broke against the coast causing very serious beach erosion and destruction of shoreline property. Many beach homes and commercial properties were damaged or destroyed. In some places the beach sand was completely washed away. Salt damage to flooded farmlands in northern Delaware is considerable.

MARYLAND

Coastal Areas___	"Mar. 5–8—The storm deepened and nearly stagnated off the Virginia Capes, giving sustained northeasterly winds for over 24 hours. Ocean City Coast Guard reported 40–45 mph wind with gusts 55–65 mph for 18 hours. The storm tide piled on top of the high spring tides to make the water up to 5 or 6 feet above normal. Four or five such high tides with 20 to 30 foot waves broke against the coast, causing serious beach erosion and destruction of shore property. Many beach homes and commercial properties were damaged and destroyed. Other property was damaged by water and sand. Nearly 1.5 million broilers and an unknown number of incubator eggs were lost due to power failure. Salt damage to flooded farmlands was minimized by the rainsoaked soil. Direct wind damage was small. Greatest and longest lasting damage is to beaches where the sand was washed away.

VIRGINIA

Eastern Shore and Tidewater areas.	"Mar. 6–8—The combination of the long fetch of strong onshore winds and the 'spring tides' caused greater wave and surf damage and tidal flooding than any other coastal storm of recent record. The islands Chincoteague and Assateague were completely covered with water and more than 1,000 residents were evacuated by military helicopters. Hundreds of homes on the beaches were totally destroyed and thousands were damaged; many residents were evacuated by boats and amphibious equipment. The fishing pier at Virginia Beach was destroyed and the largest pile driver in the world (a one and one-half million dollar machine) was turned over on its side in deep water. Hampton Roads Harbor experienced the highest tide on record for an extratropical storm, that of 5.6 feet above normal, which was less than a foot below the record tide during a hurricane of 1963. All Eastern Shore and Tidewater region was declared a disaster area by the Governor. Removal of sand by waves and tide has in many cases changed the configuration of the shoreline.

NORTH CAROLINA

Northern Coast__	"Mar. 6–8—Large and persistent low pressure storm caused greater alteration of coastline from Hatteras northward than any previous known storm, including hurricanes. Miles of protective dunes destroyed and several breakthroughs entirely across Outer Banks from Ocean to Sound. Completely new inlet 200 yards wide dividing Hatteras Island in two parts will require bridging. Miles of paved highway destroyed by washing out or buried in several feet of sand. Hundreds of beach homes destroyed or damaged, hundreds of autos submerged in water or buried in sand. Many residents evacuated by helicopter. Two elderly persons died from excitement and exposure due to rigors of the storm. Ship broke in two 100 miles off Hatteras with one person lost. Most of damage due to high water and pounding surf. Highest recorded wind gusts near 70 miles per hour, lowest barometer 29.20 inches at Nags Head. Highest tides about ten feet above mean low water with seas of about 20 ft. height. Number of persons injured estimated.

SOUTH CAROLINA

Coastal _______	"Mar. 7–9—The Great Atlantic Coast Storm of March 5–9, 1962 did limited damage in this state. Damage was mainly in the form of tidal flooding and beach erosion. Some beach cottages were destroyed, others damaged. All beaches suffered from loss of sand."

5. The Aborted Tidal Flooding of 1962 October 13

The tidal flooding of 1962 October 13 (Key No. 86) is of definite parallel interest to the preceding discussion of the 1962 March 6–7 tidal flooding. This is because the event is cyclically related to the latter perigean spring tide through the 221.5-day average period of recurring alignments. The October perigee-syzygy alignment also occurred nearly simultaneously with a very active weather disturbance along the Pacific coast now familiarly known in that area as the "Columbus Day Storm of 1962."

Although some flooding damage was experienced in connection with the near-coincidence of these events, it was nothing like that which accompanied the March 6–7 catastrophe. Contradictingly, the associated storm on the west coast was, if anything, much more severe. An entire book has been written describing the widespread effects of this natural disaster.[2]

Since an immediate question is raised as to why this case of perigee-syzygy, accompanied by a severe storm, did not produce the same marked degree of tidal flooding resulting from the very similar storm tide of March 6–7, a detailed comparison is in order. The surface synoptic weather map (fig. 66) for the date 1962 October 13 at 0100^h (e.s.t.) is included to make the analysis easier. (For the local tidal flooding effects observed around this date, see table 1.)

It is obvious from all evidence that the catastrophic effects of the 1962 Columbus Day storm on the Pacific coast were largely the result of wind damage rather than any major tidal flooding. This event nevertheless is discussed in detail here because of: (1) its local coastal flooding influences, including tidal impairment of hydrological runoff; and (2) the latent potential for extremely violent tidal flooding by the proxigean spring tides present, had the weather and wind been but slightly different.

Considering first the atmospheric low pressure system responsible for this storm, it is noteworthy that the deep cyclonic system that was located just offshore along the northern California and southern Oregon coasts on October 12 had basically a northerly component of movement and, further, that the storm center hugged the coast very closely. This low pressure center also possessed an elongated north-south axis and moved very rapidly northward parallel to the coast.

This situation provided a limited *fetch* in wind movement over the surface of the water. The coastal winds possessed directional components primarily from the south (parallel to the coast) shifting only slightly to southwesterly components inland, with their directions still channeled strongly by the north-south oriented valleys here.

Those portions of the Oregon coastline which were exposed to any onshore component of the wind are characterized by cliff topography, with no lowland portions susceptible to flooding except in small bays and estuaries.

In addition, the pressure gradient both in front of and behind the low pressure system was so steep, the alternating fall and rise in pressure as the system passed so rapid, gusting winds so prominent, and the whole system's movement over the water comparatively so brief, that the principal air-water interaction was evidenced in high waves and spindrift rather than long-period onshore swells.

The entire storm intensified and swept through coastal points, with winds shifting into directions parallel to the coast and even offshore as the storm's center moved slightly inland. The intense central core of the low pressure system was narrow and produced southerly winds along its eastern side and easterly winds along its northern extremities as it moved inland. The strongest winds in the Willamette Valley, Oreg., were from the south. The storm system and its associated atmospheric front moved almost directly northward from the vicinity of Crescent City, Calif., to Portland, Oreg., in less than 5 hours (traveling at something less than 50 mi/hr).

The storm center with its cyclostrophic winds remained just inland of the coastline during the early portion of its passage, then erratically shifted offshore again in the latter portion (see fig. 66). The entire course of this movement along the Pacific coast lasted barely 1.5 days.

Thus, in recapitulation, the comparatively low flooding potential of this storm, despite the setup tidal condition present, is attributable to:

(1) The relatively small size of the low pressure center and the fact that it did not intensify until just inland of the coast;

(2) Its general south-north path, even recurving slightly offshore in the final phases of its movement up the coast;

(3) The rapidity of movement, and corresponding quickness of dissipation of this young storm system.

This combined situation is, by strong contrast with that of the relatively slow-moving storm systems, responsible for the extensive coastal floodings which occurred on 1931 March 4–5, 1939 January 3–5, and 1959 December 29 (see the preceding discussions). Similarly, the 1962 October 13 storm is at sharp variance with the 1962 March 6–7 storm on the mid-Atlantic coast. In consequence of a high pressure system which remained almost stationary over the North Atlantic on these latter dates, blocking an active low pressure system over the ocean waters, a long fetch and strong onshore wind movement were established for 2.5 days along the mid-Atlantic coast. By contrast, the Columbus Day storm on the west coast traveled nearly 1,800 miles in 1.5 days.

6. The Tidal Flooding of 1974 January 8 (N–99)

Perhaps one of the more interesting aspects in regard to this case of tidal flooding on the west coast—produced in conjunction with a tide-amplifying astronomical alignment designated in table 22 as *extreme proxigee-syzygy*—is that it was the first such tidal event whose indicated coastal flooding potential was verified according to the principles enumerated in the present work.

The astronomical situation involved was discovered during an early analysis of the data of table 16, and its considerable potential for tidal flooding in lowland coastal regions was recognized, should strong, persistent, onshore winds simultaneously prevail.

As noted in table 16, the mean epoch of extreme proxigee-syzygy in this case was 1974 January 8 at 1200^h (G.c.t.), 0700^h (e.s.t.), or 0400^h (P.s.t.). The astronomical alignment occurred at full phase of the Moon. The separation-interval between proxigee and syzygy was -2^h, and the lunar parallax corresponding to this proxigee was 61′30.0″. The parallax indicated is especially significant in that comparable values in table 16—either equal to, or in excess of, this figure—have occurred only 29 times in the 373-year period (1600–1973) prior to this date, and 34 times in the entire 400-year period (1600–1999) of the computer printout. (The instants of proxigee are here compared, rather than the mean epochs, to ensure a maximum parallax in each case.)

The predicted tidal ranges at representative stations along the east and west coasts of the United States, for those dates displaying the largest values of higher high water resulting from this proxigee-syzygy alignment were: Boston, Mass., January 8, 14.2 ft; Willetts Point, N.Y., January 9, 10.4 ft; Breakwater Harbor, Del., January 9, 6.5 ft; Savannah, Ga., January 9, 10.8 ft; also, Aberdeen, Wash., January 8, 14.1 ft; Astoria (Tongue Point), Oreg., January 8, 11.7 ft; Los Angeles (Outer Harbor), Calif., January 8, 8.9 ft; and San Diego, Calif., January 8, 9.8 ft.

These ranges compare with corresponding values for spring ranges at the same east coast locations as follows: Boston, 11.0 ft; Willetts Point, 8.3 ft; Breakwater Harbor, 4.9 ft; and Savannah, 8.6 ft. The matching diurnal ranges for the west coast stations are: Aberdeen, 10.1 ft; Astoria, 8.2 ft; Los Angeles, 5.4 ft; and San Diego, 5.7 ft.

The buildup to this considerable increase in tide-raising force at time of proxigee-syzygy was further substantiated by cyclically related tidal flooding (Key Nos. M–98e,w) occurring approximately one anomalistic month earlier on 1973 December 11 on both the east and west coasts. (See the news article of fig. 116 which follows, describing tidal flooding along the coast of Washington in connection with the perigean spring tides near this date.) The mean epoch of perigee-syzygy in this instance was 1973 December 10 at 1230^h (G.c.t.) or 0430^h (P.s.t.). The lunar parallax at this time was 61′12.8″, and the separation-interval was $+21^h$.

Confirming the increased eccentricity of the Moon's orbit during the lunation containing the proxigee-syzygy alignment of 1974 January 8, a total *annular* eclipse of the Sun took place on 1973 December 24 at 1508^h (G.c.t.).

The Oregonian
Wed., Dec. 12, 1973
Page 24, 3M, Cols. 4, 5

Tidewaters floods Washington towns; winds to ease off

Strong coastal winds Tuesday blew water from a near-record 16-foot tide over the seawall at Tokeland, Wash., leaving water a foot deep throughout town.

Flooding caused by the tide and winds also was reported at nearby Raymond and South Bend. Police said water reached depths of four feet in the streets of the two communities. No injuries were reported.

The touchy period came between 2 and 3 p.m. at the peak of the high tide when winds of 75 miles per hour were reported at Seaside.

The wind-caused flooding at Tokeland pushed a large trailer house out into a street and washed another house off its foundation.

Waves breaking over the seawall near the general store and post office threw logs against the store and littered the road with rocks, driftwood and debris.

1973 Dec. 10
4.5h P.s.t. (+21)

M-98w

FIGURE 116.

This failure of the apparent image size of the Moon to cover the Sun because of the extreme lunar distance from Earth at the opposing exogee-syzygy position in the lunar orbit occurred very close to the mean epoch of this latter phenomenon (new moon on December 24 at 1507^h G.c.t., exogee on December 25 at 2200^h G.c.t.).

A suitable precautionary note to the public concerning the flooding potential of the astronomically amplified January 8 tides—carefully stressing the necessity of accompanying winds possessing the characteristics to induce coastal flooding—was felt desirable. The following NOAA advisory article (with two slight clarifications added here in square brackets) was released on December 26, 1973.

UNITED STATES DEPARTMENT OF COMMERCE,
WASHINGTON, D.C. 20230

NEWS RELEASE: WEDNESDAY DECEMBER 26, 1977

East Coast tides to be unusually high on Jan. 8 and Feb. 7; NOAA warns of coastal flooding if Atlantic storms occur then.

"Unusual astronomical conditions will bring high tides on January 8 and February 7, 1974, the Commerce Department's National Oceanic and Atmospheric Administration said today.

"Should these conditions be combined with severe Atlantic storms—a development which cannot be predicted at this time—extreme flooding might strike low-lying coastal areas.

"By themselves, the astronomical tides will not produce problems, weather being the controlling factor. However, similar astronomical conditions, accompanied by an offshore storm and onshore winds, generated much higher than usual water levels on March 6 and 7, 1962, which resulted in the death of 40 persons and wrought an estimated $500 million damage from Long Island, N.Y., to the Outer Banks of North Carolina.

"NOAA's National Weather Service alerted its forecasters along the Atlantic coast to be especially aware of meteorological conditions which produce 'north-easters' or other offshore storms which, if combined with the unusual astronomical conditions, could prove hazardous to low-lying areas. Other low-lying regions on the earth could be similarly affected.

"A combination of unusual astronomical conditions will occur on January 8 and February 7. On these days the moon, whose gravitational pull is the major influence on the tides, will be full, causing 'spring tides,' a higher than normal rise in the water which occurs twice monthly. But around these two particular days the tides will rise even higher than normal because of two phenomena: the moon will be 1137 miles closer to the mid-Atlantic coast on January 8 and on February 7 within 800 miles of the distance it was on March 6, 1962. In addition, the sun, whose gravitational pull also influences the tides, will be in approximately the same longitudinal plane as the moon. This alignment further enhances the astronomical effect on the tides. The earth will also be near its closest annual approach to the sun. Therefore, spring tides during these periods will be particularly high.

"The Coastal Environmental Studies Group of NOAA's National Ocean Survey has found that destructive high waters along the Atlantic coast occurred close to such extreme spring tides on April 27 and December 3, 1967 and have been traced as far back as November 2, 1861, November 1–2, 1877, and November 23–26, 1885.

" 'Should a sustained onshore wind occur during these high waters, a destructive water level could result around January 8,' pointed out Fergus J. Wood, a research scientist with the study group. 'The same could hold true also around February 7.' Wood added that similar spring tide conditions and wind-induced water crests could result in extraordinarily high tides along coastal areas around July 19 and August 17 next year, during the hurricane season.

"Wood said that his investigation reveals that in 1974 there will be an above-average number [5] of longitudinal alignments of the moon and sun which are associated with close approaches of the moon to the earth. As a result, he stated, there will be a greater than usual number of extreme spring tide situations in 1974.

"As a typical example, he cited predicted tidal conditions during 1974 at Atlantic City, N.J., which is being used as a representative test center for his studies. The [tide table] predictions are for 79 days of high tide, up to 1.3 feet higher than the normal spring tide of 4½ feet above mean low water, compared with 53 in 1954 and 1968, the greatest and least number of days of such tides during the past two decades. In 1973, the total will be 61 days and in 1975 it will be 77. Twenty-four of these days in 1974 are clustered around January 8, February 7, July 19 and August 17 when the moon and the sun will be in approximately the same longitudinal plane.

"Wood noted in a report that 'from a statistical point of view, 1974 bears close watching.' The NOAA scientist added this 'careful reservation' that 'without the association of the necessary meteorological events producing sustained onshore winds, only higher than usual high tides will be noted on these dates.'

"At Atlantic City, in March 1962, the 5.2-foot spring tide, reinforced by a 40-knot wind, with gusts to 70 knots, reached a total height of 9.5 feet above mean low water. The wind blew continuously from the sea for five consecutive high tides over a 2½-day period and that set up the conditions for the ensuing devastation. Waves as high as 20 feet were recorded on the storm-lashed shore.

"Wood stressed that the combination of unusually high spring tides and meteorological conditions could affect other coastlines around the earth to varying degrees. In the United States, he added, this would be true along the West Coast. The danger would not be as great along the Gulf Coast, except during the hurricane season, since the tides there are generally small. . . ."

A representative example of one of the conditional warnings of high tidal flooding potential which could occur in the event of supporting winds, as reported by the United Press International in the *Los Angeles Times* for December 26, 1973, two weeks before the actual tidal flooding which resulted, is given in fig. 117. A considerable number of similar rewrite articles, some not adequately emphasizing the necessity for supporting winds; others—apparently in the interests of sensationalism—positively stating that extraordinary tidal flooding would occur, were published in the news media on both the east and west coasts.

The major tidal flooding (Key No. N–99) which did occur as the result of the combination of these proxigean spring tides and supporting meteorological conditions is graphically presented in the front page article from the *Los Angeles Times* of January 9, 1974, also reproduced here (fig. 117).

A NOTE ON STORM TIDE ANNOUNCEMENT EFFECTIVENESS

Before proceeding with a more detailed discussion of the nature and extent of the coastal onslaught associated with this 1974 January 8 tidal flooding—including illustrations of the damage produced thereby—certain information-disseminating procedures encountered in connection with this event are deserving of mention. The immediate issue relates to the optimum manner of informing those segments of the general public, maritme commerce, and shoreline industry which are variously residing, vacationing, engaged in marine transportation, or conducting business activities within the coastal zone, in regard to such potentially hazardous or damaging tidal flooding conditions. Environmental, coastal wildlife preservation, and ecological interests are also deeply affected.

As indicated in the preceding section, almost no advance information was made available to the public at the time of the 1962 March 6–7 disaster. By contrast, in consequence of the ensuing advances in knowledge of tidal flooding, an overwhelming media response (including, unfortunately, some too terse misinformation) was directed toward assuring a general appreciation of the potential flooding hazards involved in the 1974 January 8 event. Somewhere between these two extremes, through a program of public education and enlightment, lies an optimum procedure for providing awareness of the necessary dependence of severe tidal flooding upon a variety of meteorological contingencies in addition to predicted tidal extremes.

One of the principal aims of the present work has been to delineate the very complex nature of a major tidal flooding and the numerous factors which go into its production. It is virtually impossible to encapsulate any proper explanation of these many variables within a necessarily abbreviated news announcement just prior to the tidal flooding.

Manifestly, it must become the responsibility of civil defense organizations, beachguards, harbormasters, the Coast Guard, beach and coastal highway preservation units, and other groups concerned with the coastal environment, as well as public safety therein, to acquaint themselves fully with the varying aspects of tidal flooding potential. At the same time, these parties should become intimately familiar with the use of marine advisory services providing other current or updated hourly data on the direction and velocity of coastal winds. These same sources also continuously monitor offshore storms which might combine with astronomically produced perigean spring tides to cause coastal flooding.

In this concept of providing continuing public enlightenment both in the resource aspects and environmental problems of the coastal zone, the New England Marine Resources Information Program (NEMRIP)—a Sea Grant project of the University of Rhode Island—

The Los Angeles Times Wed., Dec. 26, 1973 Part I, Page 4, Cols. 3–6

Moon, Sun to Produce 2 Unusually High Tides

WASHINGTON (UPI)—A rare relationship of the earth, moon and sun will cause unusually high tides on Jan. 8 and Feb. 7, and forecasters have been alerted to watch for Atlantic storms that could cause severe flooding along low-lying coastal areas.

The National Oceanic and Atmospheric Administration said Tuesday that similar astronomical conditions accompanied by an offshore storm on March 6 and 7, 1972, caused 40 deaths and $500 million in flood damage extending from Long Island, N.Y., to the outer banks of North Carolina.

Fergus J. Wood, a research scientist for the agency, said that without sustained onshore winds, only higher than usual tides would occur on Jan. 8 and Feb. 7. He said there also would be more than the usual number of particularly high tide situations in the upcoming year and "from a statistical point of view, 1974 bears close watching.

The moon's gravitational pull is the major influence on the tides. On Jan. 8 and Feb. 7, the moon will be 1,137 miles closer to the mid-Atlantic coast than usual. In addition on those dates, the sun—which also influences the tides—will be in about the same longitudinal plane as the moon, adding to the moon's effect. Further, the earth will be near its closest annual approach to the sun.

"Therefore, spring tides during these periods will be particularly high," the agency said. A spring tide is higher than normal and occurs twice a month when the moon is full.

The agency said other low-lying coastal areas also could be affected to varying degrees, particularly along the Pacific Coast . . .

1974 Jan. 8
4h P.s.t. (−2) **N-99**

The Los Angeles Times Wed., Jan. 9, 1974 (CC Ed.) Part I, Page 1, Cols. 2, 3

Giant Waves Pound Southland Coast, Undermine Beach Homes

Sandbag Barriers Erected to Ward Off Tidal Assault; Five-Day Storm Tapers Off After 7.69-Inch Rainfall

BY DICK MAIN and TOM PAEGEL
Times Staff Writers

Giant wind-driven waves riding on surging high tides battered the Southern California coast Tuesday, damaging homes and flooding nearby areas.

Occupants of many beachfront homes from Santa Barbara to San Clemente erected sandbag barriers throughout the day in preparation for the next high tide at 10:08 a.m. today.

The wave and tidal assault came as rainfall from a five-day storm tapered off after dropping 7.69 inches in the Los Angeles Civic Center.

Mostly fair weather was forecast for today and Thursday and chances of a new storm Friday, feared earlier, appeared to be remote.

Floodwaters and mud and rock slides continued to menace many low-lying areas in foothill and coastal valleys, however.

A local emergency was declared for all of Los Angeles County earlier Tuesday by the Board of Supervisors.

"Conditions of extreme peril to the safety of persons and property have arisen," the board said in its resolution.

Board Chairman Kenneth Hahn said the proclamation, which was forwarded to the state director of the Office of Emergency Services, may clear the way for state financial assistance for storm damage to public property.

In Orange County, supervisors proclaimed a "local emergency" for wave-battered coastline sections . . .

Part I, Page 29, Cols. 2

. . . At least eignt homes in the Beach Road community of Capistrano Beach, were damaged, as waves washed sand away, exposing or damaging seawalls, foundations and pilings.

Waves up to 8 feet high slammed into some Orange County beaches during the morning high tide Tuesday.

Sheriff's officers and county firemen were dispatched to endangered beach properties and helped in sandbagging operations.

Breakers wiped out wide sections of many beaches, exposing the pilings of lifeguard headquarters at both San Clemente and Newport Beach.

Part of Pacific Coast Highway was flooded in Huntington Harbor and in Newport Beach.

The morning tides are abnormally high because the present alignment of the earth, sun and moon exerts a stronger than usual gravitational pull upon the ocean.

Tuesday morning's peak tide came at 9:22 a.m. and measured 7.1 feet. A 7-foot tide is expected this morning and Thursday's tide is expected to measure 6.5 feet.

The high tides and battering waves also damaged beachfront homes in Los Angeles County, particularly in Malibu, where occupants of two residences were evacuated . . .

. . . Sheriff's deputies said earth fill was washed out from in back of two homes on pilings facing the ocean at 27036 and 27054 Malibu Colony Cove Road.

Heavy erosion was reported under homes at 25036 Malibu Road and 27308 Escondido Beach Road, but the structures were not evacuated.

Minor damage to sea walls, patios and other outdoor improvements was reported to at least three structures in the Malibu Colony.

At Zuma Beach, waves dug out much of the sandy beach, forcing lifeguards to move four portable lookout stations away from the surfline.

The high tide and waves uprooted more than 20 old pilings from the abandoned and often-burned Pacific Ocean Park pier at Santa Monica. They were towed out to sea to prevent their crashing into Santa Monica Pier.

Roger Pappas, National Weather Service forecaster, said winds which created the towering waves during high tide early Tuesday should subside by this morning, lessening chances of coastal damage.

A small-craft advisory warning of high winds between Point Conception and the Mexican border was lowered at 8 p.m.

The National Weather Service earlier said ocean swells were expected to drop from 4 to 6 feet during the night to 2 to 4 feet today and Thursday.

A storm system in the mid-Pacific which had been expected to arrive in Southern California by Friday apparently has been blocked off by a high-pressure ridge extending southward from the Gulf of Alaska, Pappas said . . .

1974 Jan. 8
4h P.s.t. (−2)
N-99

Figure 117.

publishes a monthly bulletin of ocean-oriented facts titled *Information*. In August 1975, this publication very appropriately included a communicated explanation of why flooding conditions did not materialize on the east coast of the United States in connection with the 1974 January 8 perigee-syzygy alignment, although structurally damaging tidal flooding conditions existed on the west coast:

"A continuous, strong, offshore wind tends to lower water level and negate the effects of a perigean spring tide. The one which occurred on the northeast coast on January 8 [1974] . . . was negated . . . by a combination of offshore winds and an atmospheric high pressure system. The atmosphere and the ocean . . . act together like an inverted barometer. As the atmospheric pressure rises, water level goes down; as atmospheric pressure diminishes, water level rises. The adjustment in ocean level in either direction is approximately 13 inches for each change of one inch in barometric pressure.

"Thanks to weather conditions, the east coast escaped flooding on both dates of predicted proxigean spring tides, but California did not. On January 8, 1974, giant wind-driven waves combined with extraordinary high tides battered the southern coast, creating a state of emergency."

This article also pointed up the advantages of remaining actively alert to the possibility of tidal flooding under such conditions, and of taking precautionary measures when necessary:

"Damage would have been far greater if local officials hadn't heeded NOAA's warning and taken defensive measures. Because the action of tides is world-wide, originating from the same astronomical positions, the proxigean spring tide that pounded Southern California rose four days later off the English and Scottish coasts. (Ocean water has a specific period of resonance that creates a time delay.)

"Coinciding with a strong onshore gale off the southwest coasts of England and Wales, it breached sea walls and caused widespread flooding there as well as in the outer Hebrides. On February 9 through 11, the second period predicted for perigean spring tides, conditions were also propitious and southern England was clobbered again.

"In 1962, residents of the mid-Atlantic United States had not been as lucky as they were in 1974 . . . [since] there was no warning that conditions could be ideal for disaster on March 6 and 7. As it happened, proxigean spring tides prevailed and the flood waters along the Atlantic coastline resulted in 40 deaths and $5 hundred million property damage."

Finally, the important matter of dissemination of complete and accurate information—which includes the various contingencies for tidal flooding—was brought out, reiterating and supporting the comments made several paragraphs above:

"News accounts of [the] '74 prediction alarmed the public unnecessarily . . . by oversimplifying NOAA's press release and failing to stress that onshore winds as well as high tides are required for flooding. They often failed to mention, too, that only lowland coastal regions or those with a sufficiently large daily tidal range would be affected. (Perigee-syzygy adds about 40 percent to the tidal range.) Thus the entire coast of the Gulf of Mexico and much of the southeastern coast of the U.S. would not be in danger, except during hurricanes.

"Perigean or proxigean spring tides [likewise] do not necessarily occur on the central day of perigee-syzygy, . . . but can show up within several days before or after it."

DATA ON TIDAL FLOODING AND ASSOCIATED DAMAGE

On-the-scene observations, scientific data, and photographs recorded in connection with this tidal flooding circumstance were obtained from various sources located in the coastal area between San Clemente and Ventura, Calif., which felt the greatest impact of the destructive tides. Some of the most graphic illustrations showing the extent of the damage produced (figs. 118–131), as well as extracts from official and nonofficial reports concerning the protective measures taken in an attempt to prevent this damage, have been included on the following pages.

a. The Department of Harbors, Beaches, and Parks of Orange County, Calif., for example, provided the National Ocean Survey with a copy of a preliminary but well-detailed report covering the January 8 tidal flooding. Abstracting only the appropriate technical information from this partially administrative report, the following summary is representative of the tidal flooding conditions at one of many similarly affected coastal communities, Capistrano Beach. It also demonstrates the effectiveness of well-organized protective measures applied to counter tidal flooding. It was practicable to place these into early operation in consequence of the 1973 December 26 NOAA information release—with 2 weeks' advance indication of the potential flooding threat. The prevention of extensive flooding damage despite high tides which

Courtesy of U.S. Army Corps of Engineers (Los Angeles District)

FIGURE 118.—Workers filling sandbags at Newport Beach, Calif., in consequence of NOAA forewarning of tidal flooding potential resulting from the extremely close perigee-syzygy alignment of 1974 January 8.

Courtesy of U.S. Army Corps of Engineers (Los Angeles District)

FIGURE 119.—Sandbags being emplaced at Newport Beach, Calif., as protection against the predicted extreme perigean spring tides of 1974 January 8.

were already several feet above their mean value is clearly evidenced. This record also points up the fact that, depending upon location as well as meteorological and other circumstances, the flooding effects from perigean spring tides may occur from one to several or more days on either side of the epoch of perigee-syzygy (or proxigee-syzygy) which is responsible for the astronomical portion of the unusual tidal uplift.

Courtesy of U.S. Army Corps of Engineers (Los Angeles District)

FIGURE 120.—Backfilling of the shoreline at Newport Beach, Calif., to create sand barriers during the buildup of the tidal onslaught of 1974 January 8.

Courtesy of Marine Safety Department City of Newport Beach, Calif.

FIGURE 121.—The perigean spring tides contributory to the 1974 January 8 coastal flooding event completely cover the beach and begin to intrude onto the Dory Fleet's Beachfront fish market facility, far above the normal high water mark.

Storm-Surge Damage at Capistrano Beach, Calif., January 7–9, 1974

"The storms of early January were accompanied on occasion by strong winds. These winds were especially strong on Friday, January 4 and again on the evening of Monday, January 7, with gusts of 50 miles per hour recorded at both Newport and Dana Point Harbors.

Courtesy of Marine Safety Department City of Newport Beach, Calif.

FIGURE 122.—Scene showing the encroaching sea responsible for the extreme tidal battering experienced at Newport Beach, Calif., on 1974 January 8. The municipal fishing pier is in the background; the lifeguard station is at the right. Note the severe damage to the thickly layered asphalt parking lot in the foreground.

Courtesy of U.S. Army Corps of Engineers (Los Angeles District)

FIGURE 123.—The wind-driven tidal assault of 1974 January 8 sweeps away sandbags emplaced at the lifeguard station, Newport Beach, Calif., and begins erosional breakup of the surfaced parking lot.

"The strong winds were from the southeast, causing waves to strike the shore at an angle, commonly called an upcoast angle. Indeed, in Newport Harbor, the waves came in almost directly in the harbor mouth between the breakwaters . . . .

Courtesy of U.S. Army Corps of Engineers (Los Angeles District)

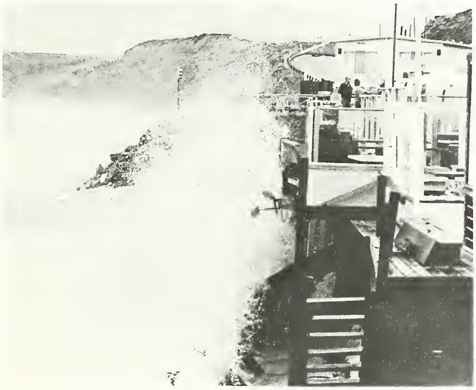
FIGURE 124.—The complete destruction of the beach front parking lot fronting the lifeguard station, Newport Beach, Calif., caused by the pounding action of the surf accompanying the extreme tides of 1974 January 8.

Courtesy of The Orange Coast *Daily Pilot,* Costa Mesa, Calif.

FIGURE 125.—Severe undercutting, subsidence, and cracking of the marina wallkway at Newport Beach, Calif., caused by high waters associated with the tidal flooding of 1974 January 8.

Courtesy of *The Los Angeles Times*

FIGURE 126.—Picture taken along the coast just west of Los Angeles, Calif., at approximately 9 a.m. on 1974 January 8, coinciding with the time of the unusually high perigean spring tide of this date.



Courtesy of The Orange Coast *Daily Pilot*, Costa Mesa, Calif.

FIGURE 127.—The augmented perigean spring tides of 1974 January 8 break destructively against the El Moro Trailer Park between Corona del Mar and Laguna Beach, Calif.

"The beach began to disappear at Capistrano Beach, and by January 7, waves were pounding against the seawalls in front of some homes there. Then on Tuesday morning, January 8, one of the highest tides of the year occurred. The approximate +7.4 foot tide was fortunately not accompanied by large waves, but because the seawalls had previously been exposed, the battle was on. The waves damaged some sections of the wall, and appeared to be undermining other sections.

Courtesy of Department of the Los Angeles County Engineer

FIGURE 128.—View from the landward side, showing extreme damage to the seawall at Malibu Beach, Calif., produced by the wind-reinforced erosion, and undercutting of the seawall from the rear caused by these augmented high tides.

Courtesy of Department of the Los Angeles County Engineer

FIGURE 129.—Dislocation of an access stile surmounting the seawall at Malibu Beach, Calif., as the result of undermining and toppling of the wall by storm-amplified perigean spring tides on 1974 January 8.

Courtesy of Department of the Los Angeles County Engineer

FIGURE 130.—View of a section of the beachfront at Malibu Beach, Calif., following the tidal flooding of 1974 January 8, showing the extensive damage to the seawall caused by wave overtopping. A closeup of the rear portion of this same seawall at a point in the center distance is included in figure 128.

Courtesy of Department of the Los Angeles County Engineer

FIGURE 131.—Detail of the breaching of the seawall at Malibu Beach, Calif., by the perigean spring tides of 1974 January 8. The deep cavitation behind the wall is produced by erosional action resulting from the overspilling seas.

"At this point, some of the residents called the Harbor Patrol for assistance. A representative was dispatched to investigate the situation. At first, it didn't look too bad, but when the tide receded and it was possible to walk in front of the seawalls, it was found that considerable erosion had occurred behind the walls, in some cases clear up under the beach side of a home.

"Due to the fact that another high tide was expected the next day and storm conditions were forecast which could result in big waves on top of the tide, it was decided that protective measures must be taken. Residents got together and obtained sandbags from the County Fire Department and began sandbagging, and also called a contractor to deliver and place large rocks in front of the seawalls. The residents also requested County assistance . . . .

"Things then happened fast. The County Departments of Communications, Road, Flood Control, Fire Protection and Sheriff were contacted. Communications dispatched a mobile communications van to the site with complete radio and telephone service, as well as portable electric generators. The Road Department sent dump trucks and drivers, which, on the way, stopped at a sand and gravel plant and picked up 50 tons of sand. Fire Protection dispatched trucks and crews for filling sandbags. Harbors, Beaches and Parks sent men, trucks and a tractor. Flooding Control sent thousands of sandbags and the Sheriff's Department provided deputies for security and crowd control.

"Almost immediately telephone lines at the District Headquarters began to ring with reporters asking questions. Eventually, crews from all three television networks would visit the site and film reports. Coverage by newspapers was complete . . . .

"An approximate 7.2 foot high tide arrived at 10:20 a.m. Pacific daylight time, on January 9. The sea was very calm, waves only 2–4 feet.

"Approximately 13,000 sandbags had been placed in front of approximately 12 homes. Generally, the bags were placed behind wooden seawalls which already existed. The day before, the sand behind the seawalls had been eroded away. In some cases, it was necessary to cut holes in wood decking or patios to gain access to behind the seawall for sandbag placement.

"One section of seawall had to be cut down, as it had been damaged to the point where the 1/9 high tide could be expected to break it loose, and then it would become a battering ram tossed about by the surf. This section was the width of one lot, fortunately the lot was vacant. During the night of 1/8 crews replaced this wall with a sandbag barrier, several bags deep and approximately 7 feet high.

"In addition, some homeowners contracted for the delivery and placement of large granite boulders in front of their seawall. Many had been put into place before the high tide of 1/9, with more to be put in after the tide recedes.

"The high tide of 1/9 resulted in no further damage. All seawalls and sandbags remained in place. As the waves rolled in, they would send surges of water to the seawalls, but they and the bags held . . . ."

b. In addition, official data were obtained from the Los Angeles office of the National Weather Service relative to the prevailing wind velocities and directions, and state-of-the-sea at the time of the tidal impact. Damage reports from coastal communities were also compiled by the Los Angeles weather station on the basis of reports from local beachguards or similar authorities which are summarized below:

As can be seen from the synoptic weather maps of the United States for 1974 January 7, 8, and 9 at 0400^h (P.s.t.) in figs. 132, 133, and 134, the contribution of wind to the unusually high tides already present was the result of a fairly shallow low pressure system (central pressure, approximately 1004 mb) approaching the southwest coast of California from off the Pacific Ocean.

The January 7 weather map indicates a warm front extending southeastward from the low pressure system. However, the absence of either an open or an occluded wave, as plotted, seems to indicate that this frontal extension did not form part of a series of "feeder" waves which often impinge on the southern California coastline, one after the other, during the winter season.

The satellite weather photos in figs. 135, 136 show the offshore situation to better advantage, and reveal that this weather front was (on January 7) an extension of an intense occluded frontal system over the southeast Pacific, and probably, indeed, part of a feeder-wave system.

The counterclockwise rotation within this low pressure center, with the surface winds blowing in northerly and northeasterly directions on the eastern side of the low, accounts for the prevailing winds from southerly and southeasterly components during the entire period of onshore movement of the system.

As shown on the January 8 map, the warm front has moved very rapidly eastward and has been modified into an occluded front. It is the strong, gusty, surface winds associated with the passage of this front which were responsible for the meteorological contribution to the storm surge experienced along the southern California coast. However, neither the surface waves nor the sea swells produced along this coast were very high, nor was their maximum height of long duration. It was the already extraordinarily high tides, driven en masse against the coastline by these short-lived but powerful winds, that caused the ensuing damage.

Marine weather observations obtained at 20 stations, ranging from Point Arguello on the north to San Diego on the south show the maximum swell height reached (at Avalon Harbor at 2000^h (P.s.t.) on January 7) to be about 7 ft; the average swell height at all other points was 4–5 ft. The peak-velocity ESE to SE winds experienced along the southern California coastline in advance of the eastward-moving low pressure center were strong and gusty, but their duration of movement over the water was relatively brief. Their velocities built up slowly during the morning and afternoon of January 7 to an average range of 15–30 knots at various locations, with continuing rain throughout the day.

By 2000^h on January 7, practically all of the marine weather stations reporting indicated wind velocities of 20 knots and greater from S to SE components, with additional gusts to 30–35 knots, and with the barometric pressure reduced to 999–1,005 mbs. During the late night of January 7, the maximum wind velocities were attained at Avalon on Catalina Island and were carried over to other coastal points. Fortunately, this period coincided with that of an extremely low water accompanying the proxigean spring tides.

The astronomical higher high water was predicted to reach 7.1 ft at Los Angeles (Outer Harbor) on January 8 at 0822^h (P.s.t.). The maximum tide height actually reached here, as reduced from marigram records, was 7.8 ft, corresponding very nearly to the time 0800^h (P.s.t.) on January 8. This value is 2.6 ft above that of mean higher high water (5.2 ft) at Los Angeles.

In a telephoned communication from the harbormaster at Avalon on Catalina Island to the Los Angeles weather station, the extreme height of the tides on the morning of January 8 was confirmed. It was stated that, at this time of higher high water, the anchor lines of the mooring buoys to which many small boats were tied (ordinarily containing some slack cable and hence inclined in the water) were standing straight up, with the buoys resembling "buttons ready to pop." It was affirmed that, had the high winds of the previous night occurred instead during this period of morning high tides, a disastrous situation might have resulted. With the water-piling action of the winds added to the unusually high astronomical tides, many of the small boats unquestionably would have been snapped from their anchor cables and have been released to drift freely around the harbor, collide with each other, or smash on the shore subject to the strong winds and currents present.

Onshore, where strong winds and very high astronomical tides did more nearly coincide (fig. 126), problems

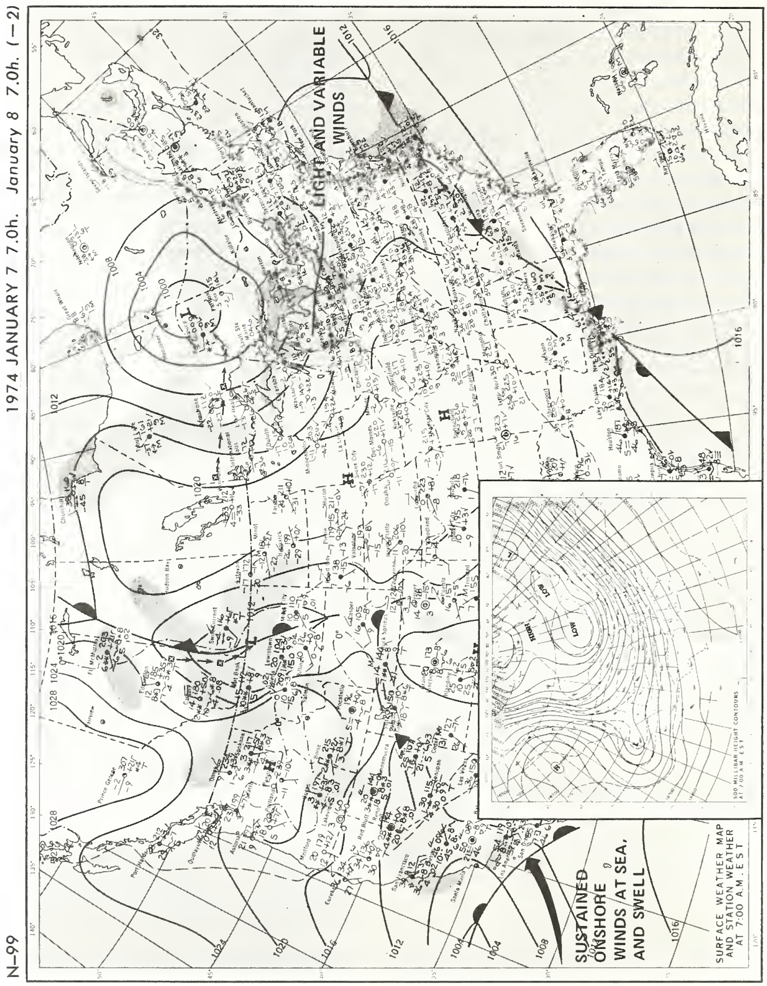

1974 JANUARY 7 7.0h. January 8 7.0h. (−2)
LIGHT AND VARIABLE WINDS
SUSTAINED ONSHORE WINDS AT SEA, AND SWELL
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T
N–99

FIGURE 132.

N–99 1974 JANUARY 8 7.0h. January 8 7.0h. (−2)

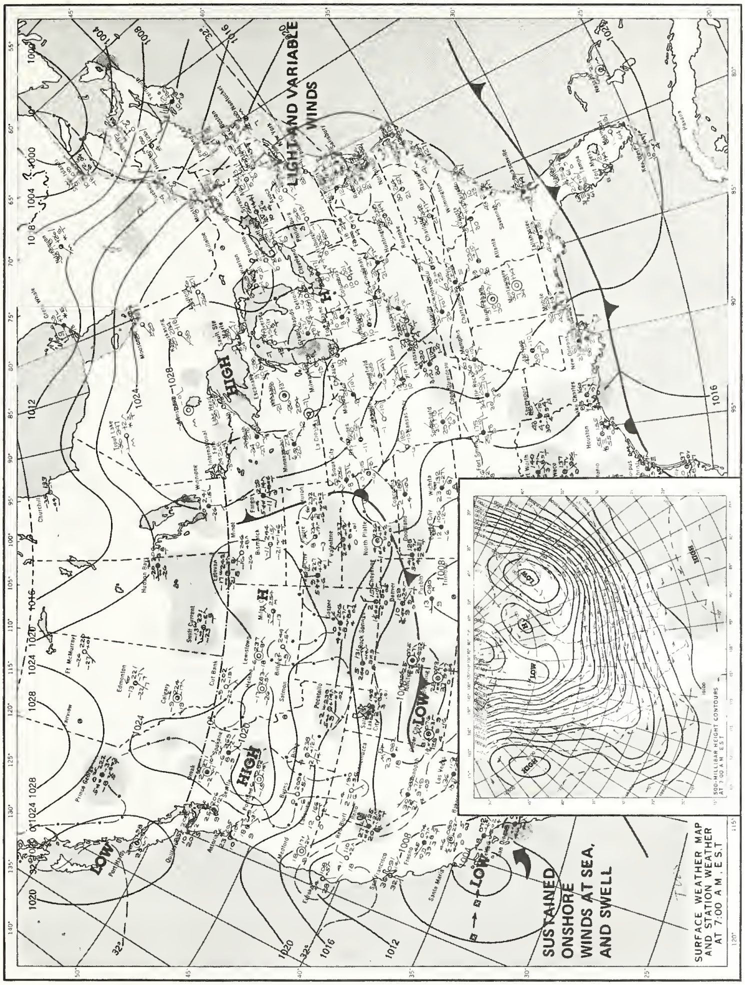


FIGURE 133.

1974 JANUARY 9 7.0h. January 8 7.0h. (−2)

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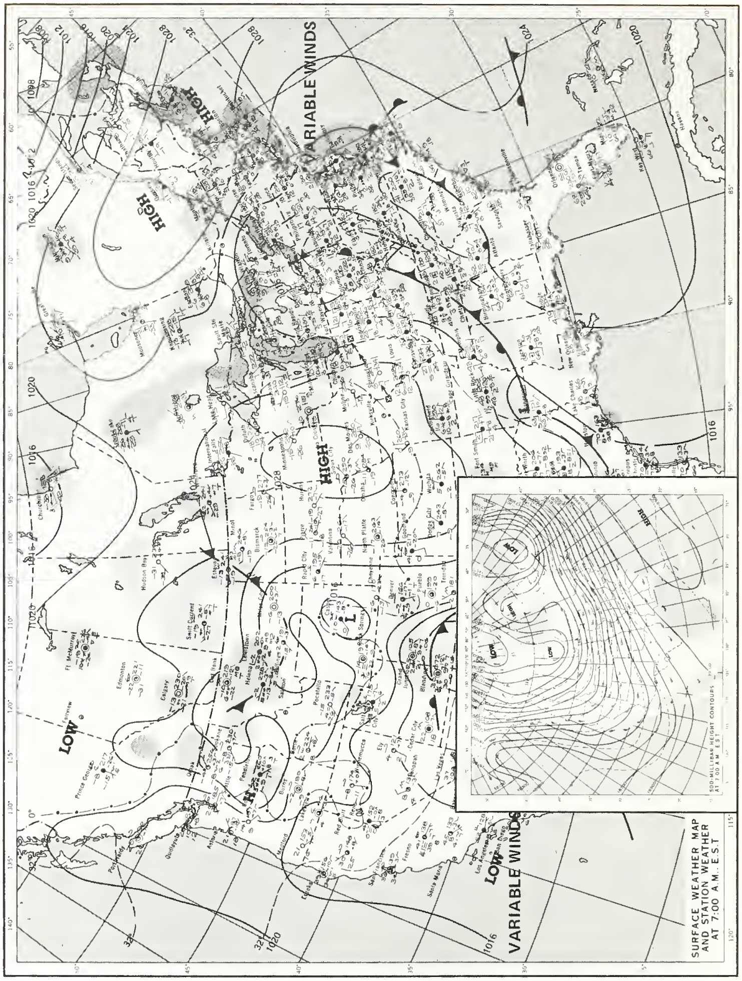
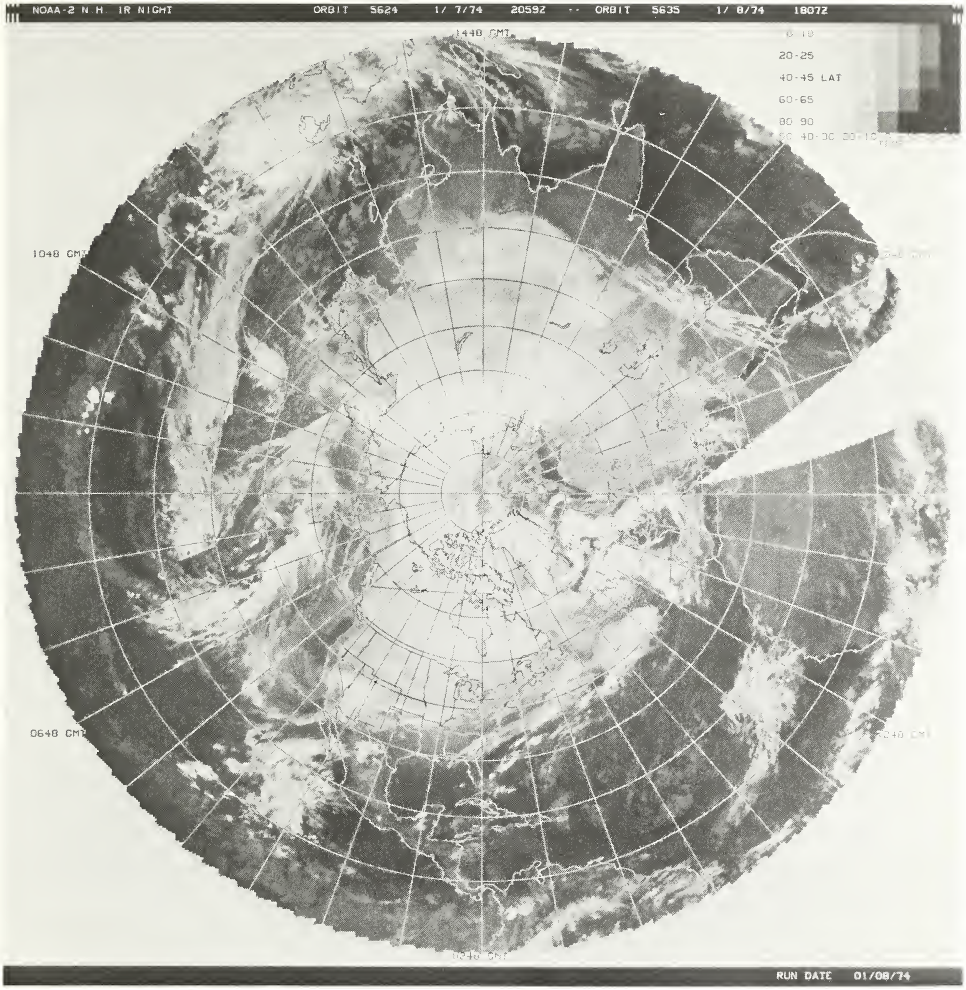


FIGURE 134.



Source : National Environmental Satellite Service, NOAA

FIGURE 135.—This composite mosaic of Northern Hemisphere cloud cover was compiled from infrared "night photography" images secured by a NOAA weather satellite during the period between 1974 January 7 1259 P.s.t. and 1974 January 8 1007 P.s.t. The approximate times corresponding to the geographic positions of satellite photography are indicated around the equatorial margin of the grid overlay. The situation represented off the Pacific coast of North America as of January 7 2248 P.s.t. shows an intense low pressure system marked by a strongly occluded frontal wave, with an associated cloud cover extending from Hawaii to the Gulf of Alaska. The southeasterly extending warm front portion of the occlusion merges into a long, recurving cold front. This joins a second warm front and together they form a second, rapidly eastwardly moving "feeder wave" whose cloud-cover effects are already noticeable over northern Baja California. (See also figs. 132–133.) Astronomically induced proxigean spring tides, raised during the early morning hours of January 8, reached their maximum heights locally along the southern California coast between approximately 0800 and 1000 P.s.t. The southerly and southeasterly winds encircling this second low-pressure system prior to the onshore arrival of the warm front (shifting to strong southwesterly winds with passage of the front) further raised the proxigean spring tides to coastal flooding conditions. Moderate swells also had been generated many miles at sea, adding to the tidal flooding potential.

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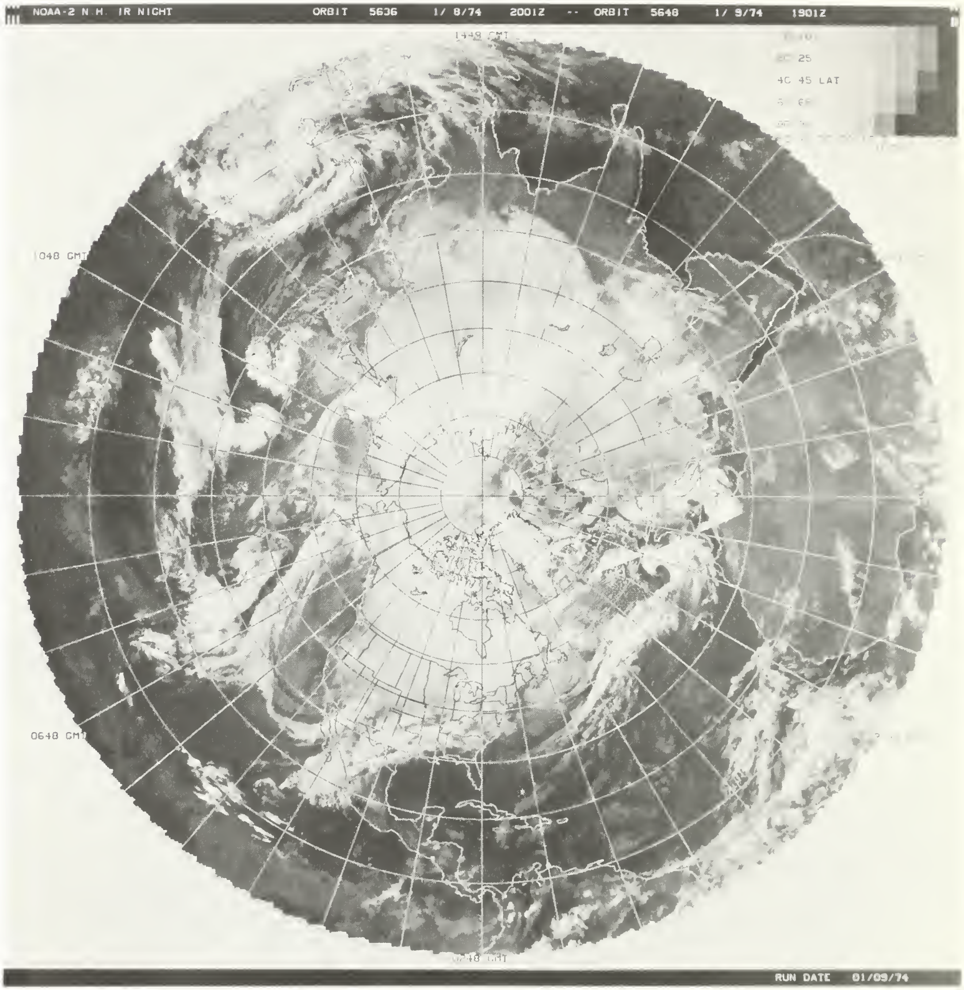


Source : National Environmental Satellite Service, NOAA

FIGURE 136.—Approximately 24 hours after the meteorological situation depicted in figure 135, the large offshore occlusion is still essentially stagnant, but the rapidly moving feeder wave which contributed to the coastal flooding already has moved over Arizona.

of another sort had arisen. Since the maximum height of the sea swell running at this time was estimated by various observers as 4–5 ft, this means that the crest of the swell would ride 2.6+4.0 or 6.6 ft above the level of mean higher high water. Assuming any seawall would be built with its base at the level of MHHW to afford maximum protection against tidal flooding, the wall would have to be at least 6.6 ft high to keep the sea from surging over its top.

As attested by the previous report in connection with Capistrano Beach, by various among the illustrations of the 1974 January 8 tidal flooding which conclude this chapter, and the summary of tidal damage at southern California coastal communities which immediately follows, such a violent overspilling and breaching of seawalls actually did happen, with consequent damage to beach homes.

c. The estimated amounts of damage caused by the unusually high tides of 1974 January 8 at various locations on the southern California coast, (See fig. 151A.) as obtained (together with related information) by National Weather Service forecasters at the Los Angeles office, were as follows:

(1) Newport Beach

(a) The first floors of 20 homes were inundated by tidal resurgence within Newport Bay, with corresponding structural damage to plaster walls, etc.

(b) A 300-ft portion of a concrete seawall collapsed.

(c) A 500-ft section of the shoreline was eroded back a distance of 120 ft along an elbow of the bay.

(d) An asphalt parking area on the seaward side of the lifeguard station was severely broken up by wave erosion and undercutting.

(e) The total structural damage to the area was estimated at $100,000.

(f) Additional damage occurred to a boat of the Dory Fleet and to the beachfront fish market facility.

(g) The measured maximum tides in this area throughout the period of tidal onslaught were 7.7–8.3 ft above mean lower low water.

(2) Capistrano Beach

(a) Structural damage was incurred to 12 homes, involving especially that caused by erosion beneath concrete foundations and damage to wooden patios.

(b) The total loss due to structural damage in the area was estimated at $25,000.

(c) A one-half mile stretch of beach also was eroded back a distance of 75 ft.

(3) Malibu Cove Colony, Malibu

(a) Erosion occurred along one-half mile of the waterfront, including overspilling and undercutting of 700 ft of seawall from the rear.

(b) Structural damage also was caused to this same seawall.

(4) Malibu Film Colony, Malibu

(a) An estimated $20,000 in damage to home properties resulted through seawater penetration, sand leaching, flooding of cesspools, downing of power poles, and overtopping of protecting bulkheads.

(b) The erosion around, and saltwater corrosion to, the steel foundation beams of two condominiums required $20,000 for their replacement.

(5) Mission Beach

A 1.7 mi. stretch of beach was eroded back a distance of 100 ft.

(6) South Laguna Beach

A 200-ft section of beach was eroded back a distance of 25 ft.

(7) San Clemente

A seashore gas main was broken by attrition due to the strong tidal action; four or five house trailers in a coastal trailer park were lost in the fire resulting therefrom.

d. As noted in the NEMRIP bulletin quoted in an earlier portion of this same section, no prominent coastal flooding accompanied the proxigean spring tide of 1974 January 8 on the east coast of the United States. The reasons are made very clear by reference to the daily synoptic weather map of the United States for this date (fig. 133).

A very large high pressure cell (central pressure 1,028 mb) was centered over the Great Lakes. The 1,024-mb isobar of this cell reached eastward as far as the Atlantic coast and extended along it from Long Island to central South Carolina. The associated clockwise circulation around a high pressure system in the Northern Hemisphere resulted in a light *offshore* wind movement at all coastal points from the Chesapeake Bay north to the Gulf of St. Lawrence. Those winds along the coast from the Chesapeake Bay south to Florida likewise possessed relatively small velocities, with components parallel to, or directed just off the shoreline, and (in the extreme south) having gentle landward components.

In addition, the eastward movement of a high pressure (1,024-mb) ridge over the middle and southern portions of the Atlantic coastline caused the pressures here to rise from that of an atmospheric "col" (1,012–1,016 mb) on the previous day. This circumstance tended slightly to depress the rising tides, by approximately 1.3 in. for each 0.1 in. rise in barometric pressure (0.1 in. of mercury rise=4.06 mb). The January 9 synoptic weather map shows that the inmoving 1,024-mb isobar was still along the coast at map time on this date, but subject to the advance of a rapidly moving, dual low pressure system and two associated cold fronts over the eastern portion of the country (fig. 134).

In the Pacific Northwest, where certain lowland portions also are susceptible to tidal flooding, a moderate high pressure system (central pressure 1,020 mb) remained relatively stationary over eastern Oregon and Washington between January 7 and January 8. Light and variable winds prevailed on this portion of the coast throughout the foregoing period.

Consequently, despite the unusually high astronomical tides present, no reinforcement by strong, onshore winds conducive to tidal flooding was provided either in the Pacific Northwest or along the Atlantic coast on January 8. A case of ordinary perigean spring tides followed this proxigean spring event of 1974 January 8 by approximately one anomalistic month. Although its perigee-syzygy separation-interval was a full -24^h, it was closely watched for tidal flooding propensities. Again, however, high pressure systems prevailed on both the east and west coasts, shoreline winds were light and variable, and flooding was not induced in the considerably heightened astronomical tides around February 6–7 (fig. 89).

In summary, three principal factors can greatly reduce, or even cancel out the rather severe damage threat to a coastline posed by the astronomical production of a proxigean spring or similar extraordinarily high tide which is subject to further uplift through the action of intense and persistent onshore winds:

(1). The substitution of a strong, sustained, *offshore* wind, resulting in a *negative storm surge,* or partial depression of the existing astronomically raised tidal waters. This occurs as the result of the amplified tidal waters being distributed toward the deeper, more open sea rather than landward, involving runup over shallow bottom slopes and channeling into constricted coastal passages.

Light to calm surface winds also usually exist in a high pressure system. Such winds have very little effect in moving (or raising) the surface waters of the oceans.

(2). An increase in atmospheric pressure prior to and/or during the period of the enhanced astronomical tidal uplift tends to depress the tide by virtue of the added weight of the overlying atmospheric column. At this same time, such a rising barometric pressure—as the result of gradual "filling" of the system and production of a smaller atmospheric pressure gradient from the high pressure center outward—is accompanied by a reduction in surface wind velocities.

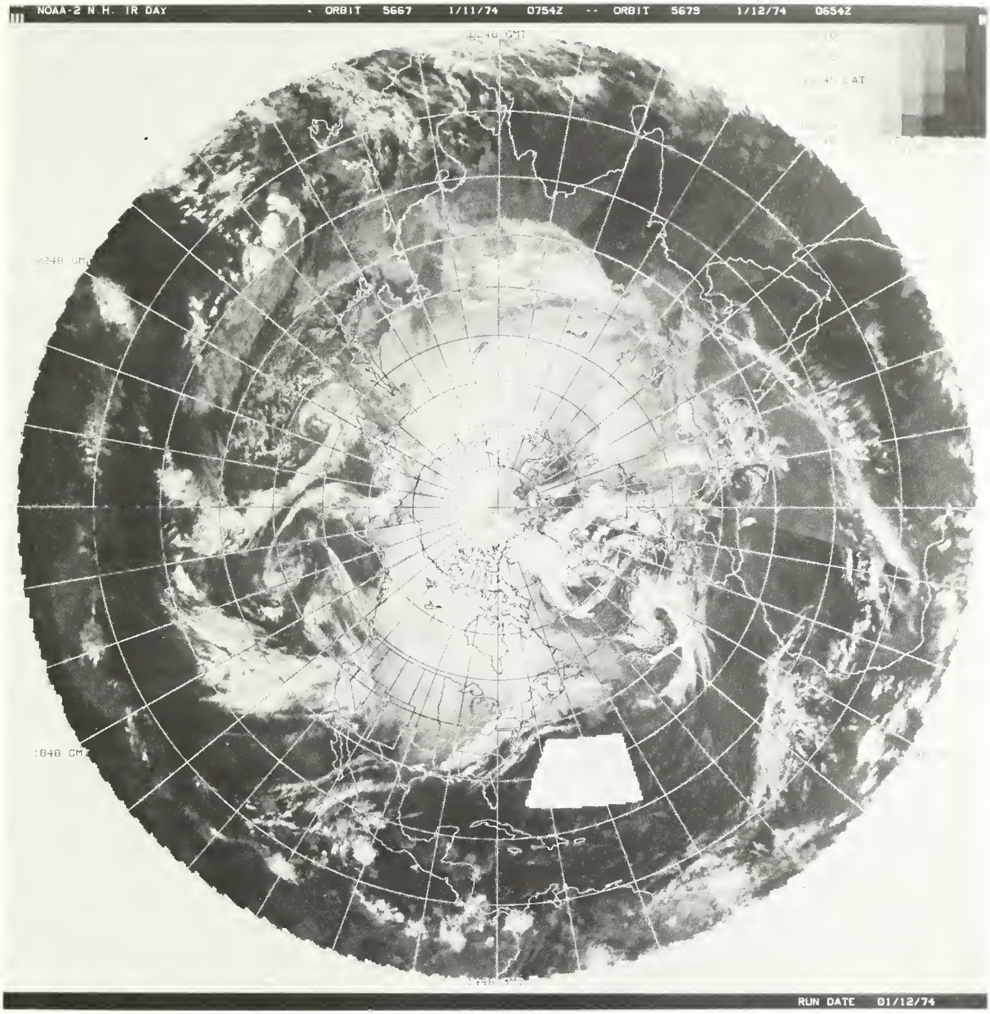
Subsidence of the air within the high pressure system rather than a vortex uplift motion which frequently occurs in an atmospheric low also tends to stabilize the air mass present and to resist the effects of cyclogenesis and frontogenesis associated with a low (both conducive to strong surface winds).

(3). As mentioned in part I, chapter 1, the addition of outlying breakwaters, organized and renewable coastal berms, dikes, dunes, and groins (artificial barriers built out perpendicular to the shoreline to resist alongshore current movements) have, in more recent years, reduced much of the severe damage caused by the combination of strong onshore winds and astronomically amplified tides. The planting and maintenance of appropriate species of saltwater-tolerant spartina grass on the slopes of barrier sand dunes located above the mean high water mark also have served as an aid against irremedial coastal erosion by these tides.

7. Tidal Flooding in the British Isles on 1974 January 11–12 and February 9

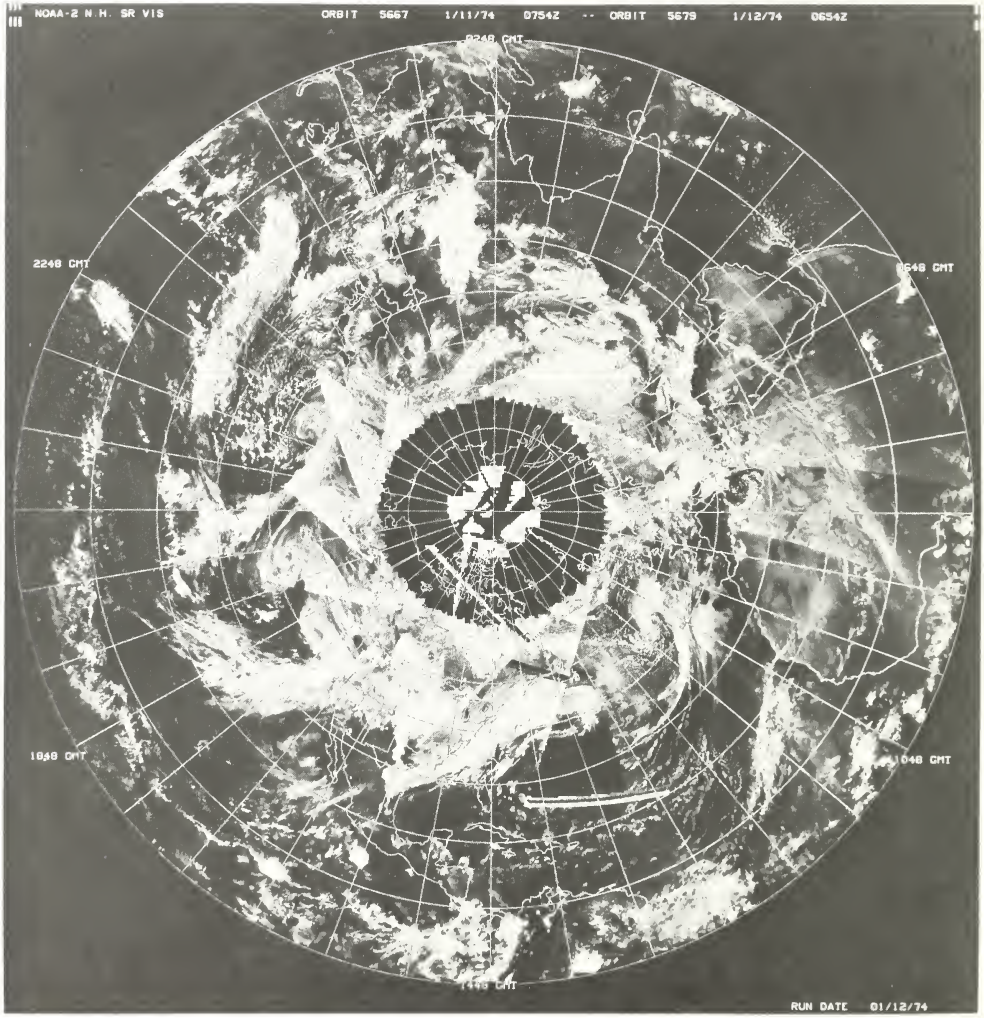
The foregoing instance of tidal flooding on the west coast of the United States on 1974 January 8 was directly related through the astronomical perigee-syzygy cycle to two other tidal floodings on the west and south coasts of Great Britain. These incidents occurred in connection with the same proxigee-syzygy alignment of 1974 January 8, having a mean epoch of 1200^h (G.c.t.), and a second perigee-syzygy alignment of February 6 at 1100^h (G.c.t.).

The actual floodings occurred on January 11–12 and February 9–11, with the already amplified astronomical tides being reinforced by the necessary strong onshore winds on these dates. This delay in the rise of maximum astronomical tides experienced in the British Isles to a date approximately 3 days later than that in which these same amplified tides became evident on the east and west coasts of the United States is caused by a dynamic phenomenon. Simply put, the ocean waters in each given locality possess a specific resonance response to their locality which, in this instance, results in the maximum tidal effects of the proxigee-syzygy (or perigee-syzygy) align-



Source: National Environmental Satellite Service, NOAA

FIGURE 137.—This photomosaic is compiled from "daytime infrared" images of global cloud cover obtained by a NOAA weather satellite between 1974 January 11 0754 G.m.t. and 1974 January 12 0654 G.m.t. (a malfunctioning signal is responsible for the blank, saw-toothed area off the east coast of the United States). A large, bent-back frontal occlusion associated with a deep low pressure center is seen to be approaching the west coast of Great Britain along a southwest-northeast track. In the eastern portion of this low pressure system, because of its steep pressure gradient strong winds would subsequently blow from the south against the southern English coast; in the warm front section of the occluded wave, winds would likewise blow from the southwest and west, directed onshore along the west coast of England. This atmospheric storm system, and the proxigean spring tides simultaneously present, were together responsible for the active coastal flooding experienced along the western and southern lowland shores of Great Britain during high tides on January 11–12.



Source: National Environmental Satellite Service, NOAA

FIGURE 138.—As subsidiary weather satellite coverage useful in nephanalysis, a Northern Hemisphere "visual image" photomosaic is included here, covering the same period of record as figure 137. This mosaic also illustrates the somewhat greater sensitivity of infrared photography in representing diffuse and peripheral cloud cover compared with photography in the visual range of the spectrum. Note the considerably sharper delineation of cloud boundaries (although cloud areas of correspondingly smaller extent) in the present figure compared with figure 137.

Courtesy of *The Stornoway Gazette, Ltd.*, Stornoway, Isle of Lewis, Scotland

FIGURE 139.—Tidal flooding at North Beach Street quay, Stornoway, Scotland, on January 11, 1974 produced by a wind-driven storm surge accompanying perigean spring tides on this date. With the quay inundated, the boats have been lifted to the level of the over-street flooding.

Courtesy of The Guernsey Press Co., Ltd., Guernsey, Channel Islands, Great Britain

FIGURE 141.—Surf breaking over the seawall at Guernsey in the Channel Islands off the south coast of Great Britain on January 11, 1974, in consequence of strong onshore winds combined with augmented tides produced by the close perigee-syzygy alignment of 1974 January 8. The arrival of the maximum perigean spring tides is affected by a composite delay resulting from approximately 3-day phase- and parallax-lags at this location. (See chapter 6.)

Courtesy of *The Stornoway Gazette, Ltd.*

FIGURE 140.—As a major spillover from the inner harbor into South Beach Street, Stornoway, caused by the storm-amplified perigean spring tides of January 11, 1974 begins to recede, business traffic resumes. The photograph was taken about 10:30 a.m.

Courtesy of *The Stornoway Gazette, Ltd.*

FIGURE 142.—Seawater lifted by the perigean spring tides of January 11, 1974 extends inland onto the wooded area at Porter's Lodge, entrance to Lady Lever Park on Lewis Castle Grounds, Stornoway, Scotland. Such an extraordinary incursion by tidal flooding was reported by *The Stornoway Gazette* to have occurred for only "the second time in living memory."

ment being felt about 3 days later in the British Isles than on the southern coast of California.

Since it is not the purpose of this treatise to intrude on the analysis of tidal waters in other areas than the United States and, to a very limited extent, Canada (many other more definitive works having been produced, with far greater local knowledge, by experts in the countries involved) this instance will be summarized in very brief terms.

The extreme bent-back atmospheric occluded front and the very deep low pressure system which produced strong onshore winds along the entire west and south coasts of Great Britain on January 11–12, 1974 is distinctively marked by the cloud-cover pattern approaching the southwest coast in the weather satellite photographs taken at 0754^h (G.c.t.) on January 11 (figs. 137–138). With these winds arriving at the same time as the amplified, astronomically produced proxigean spring tides, flooding of low-lying coastal regions was inevitable (figs. 139–142).

Seawalls were breached along the western coasts of both England and Wales, and tidal flooding extended from the District of Lewis in the Outer Hebrides on the north to Guernsey in the Channel Islands on the south. The effects of such rampaging storm surges were felt at Minehead, Somersetshire; at Appledore in north Devonshire; and at Amroth in Pembrokeshire. Coastal flooding also occurred in Devonshire at Ilfracombe, Bideford, and Lynmouth. The town of Barnstable described the flooding there as the worst in 25 years, while in Stornoway, Outer Hebrides, the tidal inundation covered a considerable section of a coastal airfield.

A similar tidal inundation occurred on the southern coast of England between February 9–11, 1974, as onshore winds reinforced perigean spring tides raised around these dates.

8. Tidal Flooding of 1976 March 16–17

This coastal flooding event (Key No. O–100) is significant as the second test case in which an accurate confirmation was made of the principles of tidal flooding potential enumerated in this work. Advance warnings also were released to responsible agencies in this instance, and appropriate flooding-protection measures were taken. (Cf. *The Boston Globe,* March 17, 1976, p. 1, cols. 2–6, and especially p. 42, cols. 1–6.)

The associated perigee-syzygy alignment ($P—S=+16^h$) had a mean epoch of 1976 March 16 at 0600^h (e.s.t.). Between March 16 and March 17, the progress of a strong, swiftly moving offshore storm (with accompanying low pressure system) was carefully monitored as its center moved northward from the New Jersey coast, some 50 miles at sea. The storm system deepened steadily in intensity as it proceeded, causing onshore winds (to the north of the low) of increasing velocity along the New England coast (fig. 143).

By the time the northern edge of the low pressure center had reached a point opposite Massachusetts, the combined tide-amplifying and storm surge effects were beginning to be felt in lowland coastal areas. Likewise, in sand embankment regions along the coast from Plum Island, Mass., to Saco and Popham Beach, Me., cottages and summer homes built on pilings overlooking the water had their foundations undercut by erosion, dropping the houses onto the lower beach or into the sea.

Tidal flooding and erosional damage was reported from such coastal communities as Marblehead, Newbury, and Provincetown, Mass.; New Castle, Rye, Hampton Beach, and Portsmouth, N.H.; and Ogunquit, Popham Beach, Saco, and Kennebunkport, Me. At Saco, the tidal flooding washed out a coastal road, destroyed a seawall, and caused an estimated $102,000 in damage to property.

Even on the afternoon of March 16, hurricane-force winds were predicted off Narragansett Bay. By the time the low pressure center reached Halifax, Nova Scotia, in its northward movement, the central pressure had dropped to about 962 mb. The system continued to intensify as it proceeded northward over Newfoundland. With storm surge effects due to the intense winds adding to the already high perigean spring tides, the eastern sides of bays and harbors near Halifax were subjected to active tidal flooding from the strong westerly winds in the southern portion of the low.

As quoted from the front page of the *Halifax Chronicle-Herald* for March 18, 1976:

". . . Unusually high tides recorded along the eastern side of Halifax Harbour and at Eastern Passage caused unestimated damage, with roads, fishing wharves, and a number of houses flooded and isolated. The high tide submerged some areas under 5 feet of water.

". . . Ferry service between St. John, N.B., and Digby as well as sailing of the ferry *Bluenose* from Yarmouth for Bar Harbor, Maine, were cancelled . . . The South Korean oil tanker *Ocean Park* was unable to dock at the Gulf Oil Refinery at Pt. Tupper because of high tides and heavy wind . . . ."

The rapid northerly movement and deep intensification of this low pressure system over the waters of the North Atlantic are described in the accompanying abstract from the *Mariners Weather Log* for September 1976.

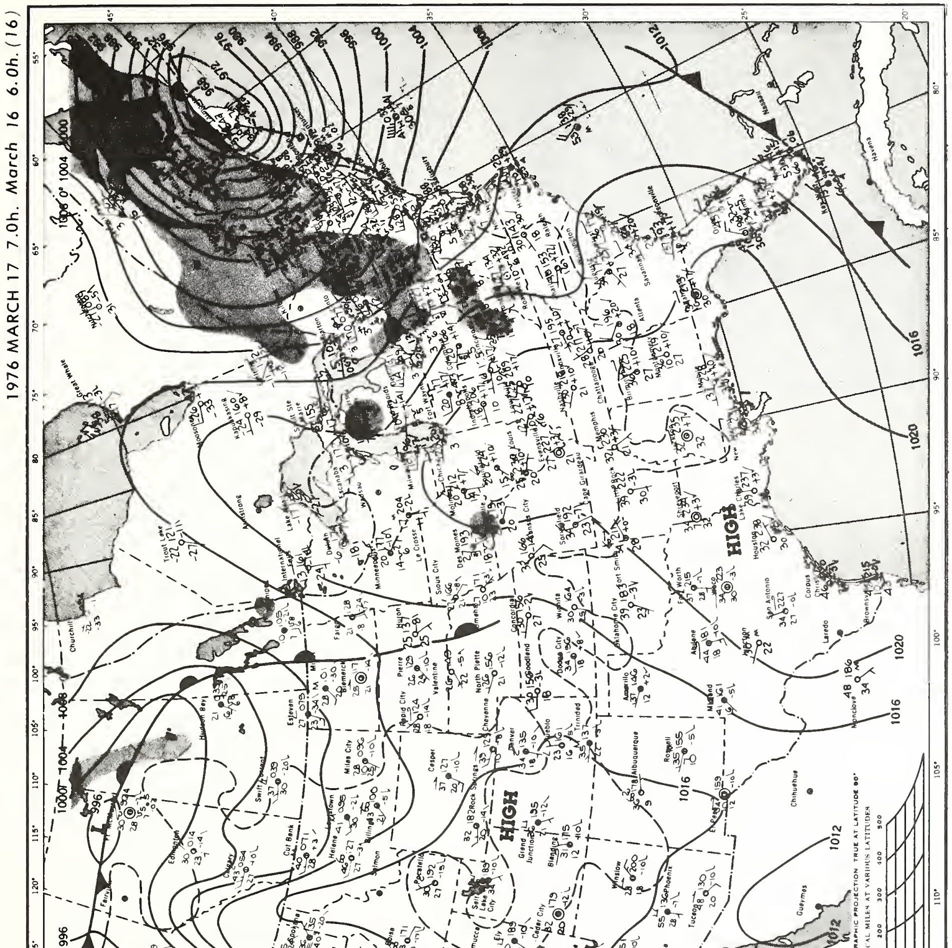

1976 MARCH 17 7.0h. March 16 6.0h. (16)
O–100
SURFACE WEATHER MAP AND STATION WEATHER AT 7:00 A.M. E.S.T.
POLAR STEREOGRAPHIC PROJECTION TRUE AT LATITUDE 60°
HIGH
HIGH

FIGURE 143.

From: *Mariners Weather Log,* Vol. 20, No. 5, September 1976

O–100—Coastal Flooding of: 1976, March 16–17, Maine to Nova Scotia

"This storm moved out of New Mexico as a frontal wave. It did not develop until late on the 16th as it approached the U.S. East Coast. By 1200 on the 17th, it was 962 mb near Yarmouth, Nova Scotia. On the afternoon of the 16th, storm warnings were issued for the New England coast with hurricane-force winds in the Narragansett Bay area. Up to 14 in. of new snow accumulated in some areas of Maine, with 20 in northern Maine. Boon Island, along the coast of Maine, reported gusts to 75 mi/h. Ships off the east coast were observing 40- to 50-kn winds with the highest being measured as 52 kn by the BIBB near 42.2° N, 65.2° W. Seas and swells of over 30 ft were reported by four ships with the highest of 35 ft by the BALTIMORE TRADER near 37.4° N., 72.6° W.

"At 0000 on the 18th, the 957-mb LOW was near Corner Brook, Newfoundland. Four ships reported 40-kn winds from Cape Cod northward. St. Pierre measured 60-kn winds. A ship at 51° N, 50° W, reported 60-kn winds just prior to passage of the occlusion. The ATLANTIC CHAMPAGNE, at 40° N, 51° W, and east of the cold front, was tossed by 20-ft seas and 28-ft swells. At 0000 on the 19th, the center was approaching Kep Farvel with a pressure of 592 mb. Ocean Weather Station Charlie measured 50-kn winds and 26-ft seas. Waves were forming on the front south of the center and moving northeastward around the perimeter. Forty knots was the strongest wind on the chart, but the ANNA WESCH reported 33-ft swells near 50° N, 42° W."

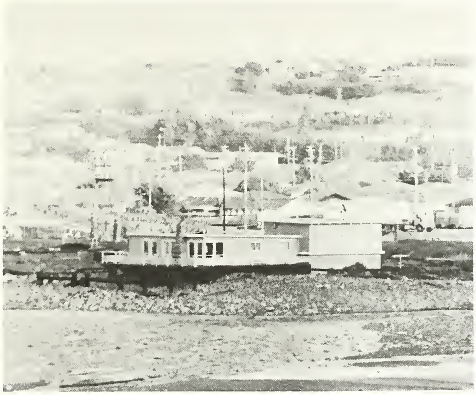
Miscellaneous scenes of perigean spring tides, photographed at both extreme high and low water, and the damage caused by such augmented astronomical tides in association with severe onshore winds and/or sea swell, are shown in figs. 144–151, on the following pages.

Courtesy of *The Pacifica Tribune,* Pacifica, Calif.

Figure 144.—The extreme low water occurring during the negative-amplitude phase of perigean spring tides on 1962 October 13. The scene is photographed from offshore at Pacifica, Calif. The vastly greater amount of beach exposed at such extreme low waters is a boon for marine biologists, marine archaeologists, beachcombers, and certain engineering projects. At the same time, however, very shallowly submerged reefs, rocks, and bottom slope present a hazard to navigation.

Courtesy of *The Pacifica Tribune,* Pacifica, Calif.

Figure 145.—A matching scene photographed from the same location during the extreme high-water phase of these perigean spring tides. Despite a protecting seawall, the beach cottage shown already has been flanked by the incoming tide and is in danger of serious flooding.



Courtesy of *The Pacifica Tribune,* Pacifica, Calif.

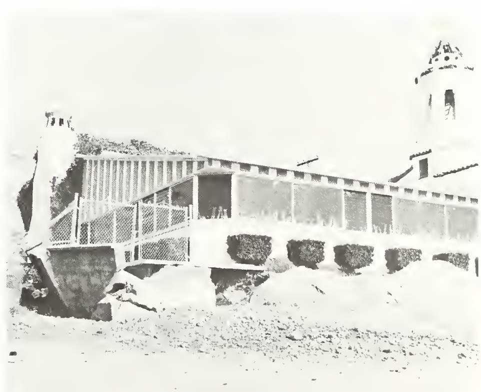
FIGURE 146.—A second view looking slightly to the left of figure 144 during the extreme low water on this same date, showing the large extent of foreshore uncovered. The existing stream drainage channel in the foreground is seen to be completely unimpaired, permitting free hydrological runoff of rainfall or other surface waters to the sea.

Courtesy of County of Ventura, Calif., Public Works Agency

FIGURE 148.—Representative damage to porch and front of beach home at Oxnard Shores, Oxnard, Calif., caused by wind-impelled waves and swell piling on top of perigean spring tides resulting from a perigee-syzygy alignment on 1971 March 26.

Courtesy of *The Pacifica Tribune,* Pacifica, Calif.

FIGURE 147.—Corresponding view from the same position as figure 146, photographed during the high-water phase of the tides. The drainage outlet to the sea is now completely covered and blocked by the incoming tide. Thus, whereas sometimes perigean spring tides do not result in actual salt-water inundation, the impairment of strong hydrological runoff by such extraordinarily high tides can cause the backup and/or overflow of normal drainage channels into surrounding areas.



Courtesy of The Orange Coast *Daily Pilot,* Costa Mesa, Calif.

FIGURE 149.—Damage to the seawall and protecting parapet at Capistrano Beach Club, Capistrano, Calif., consequent upon the wind-reinforced amplification of already high waters produced in association with the perigee-syzygy alignment of 1962 February 5. (See table 16.)

Courtesy of The Orange Coast *Daily Pilot*, Costa Mesa, Calif.

FIGURE 150.—Detail of destruction of the concrete walkway and driveway at Capistrano Beach Club resulting from erosion and attrition of the underlying foundation materials by storm-amplified perigean spring tides occurring around the 1962 February 5 date.

Courtesy of County of Ventura, Calif., Public Works Agency

FIGURE 151A.—Section of the coastline in Ventura County, Calif., photographed on January 8, 1974 during the coincident arrival of wind-driven surf and perigean spring tides associated with the close perigee-syzygy alignment of this date. Note the extensive log debris in the foreground and the fact that waves are pounding against fenced areas normally well above the waterline.

It is significant in terms of a further verification of the principles of tidal flooding potential enunciated in this work to include four other examples of severe tidal flooding which took place subsequent to preparation of the preceding text covering the period 1635–1976. These more recent examples are especially noteworthy since, in appropriate pairs, they occurred nearly simultaneously on the east and west coasts of the United States, exactly one anomalistic month apart. The respective cases, happening in 1978, are outlined below. Additional information regarding the full extent of the flooding damage sustained and the exact times and locations of these flooding events may be had from the newspaper sources cited in each instance.

9. The Tidal Flooding of 1978 January 8–9

On 1978 January 8–9, severe coastal flooding obviously related to perigean spring tides was experienced, in turn, along both the coast of southern California and the southeast coast of New England—and, 3 days later, on the west coast of Great Britain. Interestingly, this circumstance was, in the latter respect, very nearly a repetition of the tidal flooding of 1974 January 8 described earlier in this same chapter.

The 1978 flooding event was directly associated with an alignment between perigee and syzygy having a mean epoch of January 8 at 1500^h (e.s.t.), for which $P-S = -16^h$, $\pi = 61'18.2''$. As the result of the particular oceanic resonance factors appropriate to the west coast compared with the east coast, major tidal flooding occurred in connection with these perigean spring tides one day earlier in the former location, aided by coincident strong onshore winds. These winds were generated in conjunction with a long, southward-extending, cold-front portion of an occluded atmospheric wave centered in a deep low pressure cell over the Gulf of Alaska.

Particularly hard hit by tidal flooding in the lowland coastal regions of southern California were the beaches at El Segundo and Manhattan, as well as numerous others between Malibu and Ventura. At many such locations, sandbagging was resorted to, but failed to stem the incoming tides and storm-raised surf on January 8. Very extensive damage was caused to seawalls, homes, and beachfront property in these areas. (See the *Los Angeles Times,* Monday, January 9, pt. I, p. 1, col. 4; p. 3, cols. 1–4.) Considerable flooding damage also was experienced at Mission, South Mission, La Jolla, Ocean, and Del Mar beaches. (See *The Evening Tribune,* San Diego, January 9, p. 1, col. 5; p. 6, cols. 1–2.) These initial instances of tidal flooding were succeeded on January 9 by further tidal inundation at Malibu, Rincon, and Solimar beaches as well as, further north, at Seacliff State Beach and Capitola. (See the *Los Angeles Times,* January 10, pt. I, p. 1, cols. 3–4; p. 3, col. 4; p. 19, cols. 1–4.)

Because of the average 0.5^d–1.5^d phase- and parallax-ages on the east coast, perigean spring tides prevailed here on January 9. And, successively, along the entire Atlantic coast from Virginia to Maine, these tides were accompanied during the period of their rise by strong onshore winds produced in the northern portion of a deep low pressure system which moved up the coast from the south.

Tidal flooding and/or severe erosion of the coastline was felt prominently at Provincetown, along Cape Cod, and at Revere Beach, Mass., during the times of high tides on January 9 (see the *Boston Evening Globe,* January 10, pp. 1, 8); also at Southampton, Long Island, and the Rockaways, Queens, N.Y., and in various other coastal lowland regions between Virginia and Maine. (See the *New York Times,* January 10, p. 20, cols. 2–6; p. 25, cols. 5–8).

In keeping with the individual resonance factors peculiar to the west coast of Great Britain noted in example 7 of this same chapter, the effects of these augmented perigean spring tides, raised further by strong onshore winds, were felt 3 days later in various coastal regions. The gale- to near-hurricane force winds (gusting to 82 mph at London) were produced by a steep atmospheric pressure gradient between a 1,032-millibar high pressure system in the eastern North Atlantic and a 892-millibar low pressure cell over the north of Europe. (See *The Times,* London, England, Thursday, January 12, p. 2, cols. 5–7.)

High tides breached seawalls at Cleethorpes in Humberside, and invaded the town. A portion of a road at Ilfracombe on the north Devon coast was washed into the sea by the combination of high tides and heavy rainfall. Other tidal flooding occurred at Rhos-on-Sea in Colwyn Bay, Clwyd, and at Llanfairfechan, Gwynedd. A coastal road at Sandgate in Kent was closed by the coastal innundation. (See *The Times,* London, January 12, p. 1, cols. 5–6.) Elsewhere, the effects of these exceptionally high astronomical tides, coupled with strong storm winds, were observed on the Thames River, England, which came within 19 inches of breaching its floodwalls, and in wave and tidal flooding which surmounted dikes in Belgium. (See the Reuters dispatch in the *Los Angeles Times,* January 13, pt. I, p. 7, cols. 5–6.)

10. The Tidal Flooding of 1978 February 6–7

Yet another confirmatory instance of coastal flooding produced by perigean spring tides in conjunction with supporting onshore winds—which is also indicative of a series relationship between such tidal flooding events and the times of successive perigee-syzygy alignments—came, significantly, exactly one anomalistic month later, on 1978 February 6–7. Again, the situation is made more meaningful in strengthening previous evidence with regard to the significant role of perigean spring tides in coastal flooding by a nearly coincident occurrence of tidal flooding on *both* the east and west coasts of the United States.

In this case, a pseudo-perigean spring tide (defined according to the terms of reference given earlier in this chapter) was produced by a perigee-syzygy alignment whose mean epoch was 1978 February 6 at 1300^h (e.s.t.), with $P-S=-42^h$. This astronomical circumstance was accompanied, on the east coast of the United States, by a violent storm which has been variously described as everything from "the worst storm in 30 years" to "the most severe storm ever to strike New England," depending upon the particular location affected. At Cape Cod, wind velocities as high as 92 mph were recorded. As in the January 9 case, the shoreline flooding consequent upon wind-driven high tides was felt in coastal lowlands from Virginia to Maine on February 6–7. (So severe was the resulting damage that, for some days, local newspapers were unable to publish or distribute their regular editions. But cf., the *Los Angeles Times,* Wednesday, February 8, pt. I, p. 1, col. 1; p. 29, cols. 1–5; February 12, pt. I, p. 1, cols. 1–2; p. 6, cols. 1–3.)

The sections hardest hit by tidal flooding were those around Revere, Scituate, (See fig. 151B.) Hull, Salem, and Winthrop, Mass. In Revere alone, an estimated 2,000 homes were flooded. At Monmouth Beach, 85 families were evacuated, and at Winthrop, 50 families had to be reached by amphibious vehicle. At Revere, 20-ft tides topped the seawall, and were prevented from returning by the rising high waters. Also feeling the flooding effects of the high tides on February 6–7 were Falmouth, East Falmouth, Woods Hole, Eastham, and Rockport, Mass. Other extensive tidal flooding occurred at Belman, Sandy Hook, Sea Bright, and Monmouth Beach, N.J., and at Coney Island, N.Y. The Cape Cod coastline suffered very damaging beach erosion. Tidal flooding damage likewise was heavy along the southeastern coast of Maine. It has been estimated that, throughout the entire coastal region of New England, 11,000 persons were forced to leave their homes due to the flooding waters. [See *The Boston Herald American,* February 9, p. 1 (entire page); p. 2, cols. 5–6 (pictures); p. 3, cols. 1–4; p. 4 (entire page); also this same newspaper's Storm Souvenir Edition under "The Flooding," pp. 7–13 (pictures. Cf., further, *The San Diego Union,* February 9, p. A–3, cols. 1–4 (pictures); p. A–14, cols. 4–8.]

This tidal flooding on the east coast was matched on the west coast on February 6–7 by major tidal flooding resulting from exceptionally high tides coupled with pounding waves and surf. The latter two conditions were created by successive storm fronts associated with a series of inmoving meteorological "feeder waves" from off the Pacific Ocean. And, in a manner similar to that demonstrated one anomalistic month earlier, the astronomically elevated tides, reinforced by gale-force winds, swept over protecting sandbag barriers at Surfside, Sunset, and Seal beaches, Calif. Tidal flooding also occurred along Balboa Peninsula, on Balboa Island, and at Pacific Beach. Severe tidal erosion was encountered at South Mission Beach. (See the *Los Angeles Times,* February 8, pt. I, p. 1, col. 5; p. 32, cols. 1–3.)

Such recurring coincidences between perigean spring tides and violent coastal storms possessing strong onshore winds capable of supporting severe tidal flooding—as evidenced throughout history, and often occurring on *both* coastlines simultaneously—is a scientifically intriguing circumstance. From evidence at hand, these coincidences appear to exceed a normal probability distribution, considering the far greater number of occasions within each year when such strong onshore winds could occur other than in the relatively narrow "windows" of perigean spring tides. The seemingly above-average frequency of such concurrent events raises the question whether some possible interrelationship between the respective astronomical (gravitational) and meteorological phenomena might exist which has not as yet been established. From the available, documented occurrences, a certain statistical relationship also seems to hold between the most severe cases of tidal flooding and the second or third alignment in a given perigee-syzygy series. Under these latter circumstances also, repeated flooding events often occur within consecutive anomalistic months. These and other yet unproven astronomical-geophysical issues will receive further attention in chapter 8.

Photocredit : *The Boston Herald American*

Figure 151B.—Section of shoreline at Scituate-Marshfield, Mass., showing the extensive tidal flooding damage to homes caused by the combination of strong onshore winds and the elevated perigean spring tides of February 6–7, 1978 associated with the pseudo-perigee-syzygy alignment of 1978 February 6, $P-S=-42^{h}$. (See item 10.)

Chapter 8.

Tidal Flooding Potential, and the Relationship of Perigee-Syzygy to Other Oceanographic and Geophysical Factors and Influences

The data of table 1, the news accounts contained in table 5, and the detailed evidence of chapter 7 provide ample support to a strong positive correlation between perigean spring tides and coastal flooding, when these tides are accompanied by the correct conditions of wind. The many examples of tidal flooding previously cited also indicate that a considerable multiplicity exists among the astronomical conditions of perigee-syzygy which are capable of raising tides to the point of vulnerability to attack by strong onshore winds.

The changing right ascensions, declinations, orbital angular velocities, and distances of the Moon, when subject to correspondingly varying dynamic conditions imposed during each revolutionary period and the perturbations produced in the lunar orbit by the Sun, themselves result in a diversity of tide-raising forces at times of perigee-syzygy.

In addition, the reinforcing gravitational forces of both the Moon and the Sun are involved in the production o. unusually high tides at these times. Add to the Moon's complexities of motion (1) those of the Sun's apparent motion due to the annual revolution of the Earth, and (2) further modifications affecting the attraction of the Sun upon the Moon caused by the Earth's changing heliocentric distance in its elliptical orbit—and the variety of circumstances of perigee-syzygy builds up accordingly. The magnitude of the combined lunisolar tide-raising force also can vary at perigee-syzygy alignments occurring at different times of the year. Finally, the fluctuating velocity of the Moon at different points in its orbit, and the particular component of this velocity measured parallel to the Earth's Equator, are of importance in the production and duration of perigean spring tides.

In columns 5–6 and 11–12 of table 16, four sets of figures have been included for each case of perigee-syzygy whose meaning has not yet been fully explained. These data, examined analytically, incorporate the effects of at least the majority of the above-mentioned factors and, in so doing, provide a quantitative measure of the gravitational forces tending to amplify the astronomical tides. Grouped in consecutive pairs, they constitute the astronomical portion of an index of tidal flooding potential.

An unusual proximity of the Moon to the Earth, together with a corresponding variation in the tide-raising force inversely as the third power of the distance, is the most important single determinant in raising the tides to a significantly higher level. However, the use of the geocentric horizontal parallax of the Moon is not the most representative astronomical indicator of tidal flooding potential. Moreover it has been repeatedly pointed out that an increase in the interval of time during which these near-maximized forces act also plays a contributing role in augmenting the tide-raising influence. It thus becomes necessary to select, as an appropriate coefficient, some indicator which combines the distance, velocity, declination, and relative inclination of the Moon's motion with respect to the celestial equator (thus allowing for amplified tidal duration effects) and which includes the influence of the Sun's gravitational attraction as well. Such a composite astronomical index to tidal flooding potential, known as the $\Delta\omega$-syzygy coefficient (or $\Delta\omega$-S) will be proposed in the present chapter. In this particular usage, $\Delta\omega$ represents a comparative measure of the changing orbital angular velocity of the Moon, selectively referenced to (1) perigee, and (2) the vernal equinox, and including the effects of numerous other astronomical factors.

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Certain necessary qualifications and restrictions on the universal application of such a coefficient, related to the existing type of tides, a limited daily range, or a predominant solar modification of the harmonic constituents at a given locality—as well as other special exceptions resulting from geographic and hydrographic considerations—are also presented.

Development of a Numerical Index Designating the Astronomical Potential for Tidal Flooding

In establishing some quantitative measure of the possibility of any one perigean spring tide producing coastal flooding when accompanied by the requisite wind conditions—and hence the flooding potential of one perigean spring tide compared with another—the astronomical circumstances present must be individually evaluated. The four principal conditions affecting the production of all categories of perigean spring tides are: (1) a closer proximity of the Moon to the Earth as a result of (a) solar perturbations of the Moon's orbit when the Sun in its apparent motion approaches coincidence with the line of apsides (in this case, specifically, the perigee position) and (b) a smaller separation between perigee and syzygy produced by a closer commensurability between the synodic and anomalistic months under certain conditions; (2) the effect of changing declination upon the Moon's component of motion in right ascension; (3) the longer interval of time required for a point on the rotating Earth to catch up with the physically advanced positions of lunar transit resulting from accelerated orbital motions of the Moon at the time of perigee-syzygy; and (4) the retrograde motion of perigee at this same time.

The varying distance of the Sun from the Earth is also relevant in terms of the increment of *force* acting on the Earth's waters at perihelion; however, as has been seen, at solar perigee the Moon's orbital velocity is decreased and the Earth's necessary rotational catch-up motion is reduced.

Among all of the tide-raising factors present, the Moon's distance from the Earth has the greatest influence in producing a significantly amplified rise of the tides. It might readily be assumed, therefore, that the use of the Moon's instantaneous parallax as interpolated from *The American Ephemeris and Nautical Almanac* for the various occasions of close perigee-syzygy might be the most logical single indicator of tidal flooding potential associated with such astronomical alignments. This is not the case.

An increased value of the lunar parallax does represent the reduced distance of the Moon from Earth at perigee-syzygy in a closely matching fashion. However, this quantity as tabulated in the ephemeris does not represent the corresponding effects of changing orbital velocities of the Moon with distance from the Earth, the influence of the changing lunar declination in this same connection, nor the combined (coplanar) tide-raising actions of the Moon and Sun. Neither does it in any way indicate the corresponding requirements for catch-up motion by the rotating Earth, and resulting extensions in the duration of time over which stronger gravitational forces act, consequent upon any given perigee-syzygy alignment. Similarly, the value of ρ, the radius vector from the center of the Earth to the center of the Moon, which is numerically equal to cosecant π, is not a useful indicator for the present purpose.

1. The Need for Combined Lunisolar Representation

In assigning some quantitative measure to the increased potential for tidal flooding resulting from the astronomically amplified higher waters at times of perigee-syzygy, the preceding factors and failings must be taken into account. It is obvious that it is necessary to find some coefficient which includes the dynamic effects of both the Moon and Sun, since the gravitational forces of both are involved. The increase in tidal range due to the alignment of Moon and Sun at syzygy has been shown to be about 20 percent, and that due to the approach of the Moon to the Earth at perigee amounts to another 20 percent. Accordingly, the combined gravitational forces of the Moon and Sun at times of perigee-syzygy are, on the average, responsible for an increase in tidal range of about 40 percent above the mean spring range.

As derived from *The American Ephemeris and Nautical Almanac*, daily apparent angular velocities of the Moon and Sun in celestial longitude (λ) or in right ascension (α) are basically a function of: (1) their respective parallaxes; (2) their instantaneous and changing declinations (δ), and (3) the actual or real (as well as perturbationally disturbed) motions of the Moon and the Earth, respectively. All three of these factors are among those whose effects are being sought after for consolidation in a single index of enhanced tide-raising activity. The daily motions of the Moon and Sun in celestial longitude must, therefore, be regarded as useful indicators in the task of finding such a meaningful index of amplified astronomical tide-raising force and associated tidal flooding potential. Of even greater significance in the first case, however, is the angular motion of the Moon in its own orbital plane. The daily apparent motion of the Moon in right ascension becomes an equally valuable indicator for the present purpose, since the Moon's angular motion is thereby referred to the plane of the celestial equator. Significantly, this is also a plane perpendicular to the axis of the Earth's rotation—and that plane in which the frequently described catch-up effects of the Earth's rotation must occur.

2. Significance of the $\Delta\omega$-Syzygy Coefficient

In the light of all aspects of the preceding discussion, it is apparent that the necessity exists for the establishment of some quantitative indicator which represents not only the increased gravitational effects of the Moon on the Earth's tidal waters caused by the reduced separation between them at the time of perigee, but also: (1) the combined gravitational forces of the Moon and Sun at (perigee-) syzygy; (2) the increased tide-raising force of the Sun exerted at solar perigee; and (3) the enhanced tidal forces introduced by a coplanar alignment of the Moon and Sun in declination. It must also include the various effects, at perigee-syzygy, tending to lengthen the periods of time during which the previously mentioned augmented gravitational forces exert their influences, and the special significance of the retrograde motion of perigee. Such a numerical quantifier is achieved, in part, through the determination of the *rate of closure* of the Moon's angular motion in orbit with respect to the position of perigee. Because the Moon's velocity of revolution is always far greater than the angular motion of perigee along the orbit as the result of solar perturbations, the Moon will in every case be catching up on the position of perigee. Expressing the appropriate angular velocities as differential rates of motion in one day of time, as a first component of the total expression for $\Delta\omega$-S, the relative motion $\Delta\omega_1$ of the Moon with respect to perigee is given by:

$$\Delta\omega_1 = \dot{\nu}_{☾}, - \dot{\varpi}_{☽}$$

where $\dot{\varpi}_{☾}$ represents the rate of angular motion of perigee (or rate of angular change in the true anomaly) and $\dot{\nu}_{☾}$ the rate of angular motion of the Moon. Both motions, expressed in degrees per day, occur along the Moon's orbital plane.

The selection of these particular parameters permits representation of:

a. The lunar parallactic effect: The increased orbital angular velocity of the Moon as a function of close proximity to the Earth at the time of perigee- (or proxigee-) syzygy—this reduced separation being caused by the solar perturbational influences exerted on the Moon's orbit by the perigee-syzygy alignment.

(The magnitude of this component of the $\Delta\omega$-S coefficient therefore bears a direct relationship with the increased values of the lunar parallax at times of perigee-syzygy.)

b. The motion of perigee: Of particular importance is the maximum retrograde motion of perigee which occurs as the Moon reaches the position of perigee-syzygy. This effect will be evident as an increase in the rate of closure between the Moon and perigee, since the two are moving in opposite directions. The *relative* velocity is, therefore, represented by the vector sum of the two velocities, whose magnitude will always have its greatest value at the time of perigee-syzygy (see pp. 177–182).

c. The solar parallactic effect: This negative velocity of perigee is further augmented at the time of perihelion by an added lunar proximity to the Sun and an increase in the perturbational influences consequent upon the heightened solar gravitational force present. The value of the rate of closure will increase accordingly, providing an indication of the effect of solar perigee.

d. The effect of the annual equation: Conversely, the reduction in the Moon's velocity near the time of solar perigee caused by perturbational influences will, of its own accord, be reflected in a diminished relative velocity between Moon and perigee. Thus, in its total effect, proximity to solar perigee will be represented by the *net difference* between c and d. Since the effect of c is always larger, the resultant influence will always be an increased value of $\Delta\omega_1$.

e. Coplanar lunisolar alignment: A coplanar alignment of the Sun and Moon in declination, or the possible joint alignment of these bodies in declination and longitude at the equinoxes, are both conditions which create increased gravitational forces. The corollary production of an augmented lunar parallax is manifest, in turn, by an increase in orbital velocity of the Moon, and hence a larger value of the $\Delta\omega_1$-S coefficient.

Thus, in each of the above cases, the $\Delta\omega_1$-S coefficient responds directly to those factors whose existence produces an enhancement of the tide-raising forces on the Earth's waters. A large value of the $\Delta\omega_1$-S coefficient is directly indicative of conditions which are conducive to an increase in such tide-raising forces.

Of considerably less consequence in its influence, and subsequently so weighted, a second component of the total $\Delta\omega$-S coefficient is required in order to include the effects of a lengthening of the period of increased gravitational force associated with each alignment of perigee-syzygy. Such prolongations of the intervals of tide-raising force application result from the necessity for equivalent catch-up motions by the rotating Earth to compensate for increased orbital motions in right ascension at the time of perigee-syzygy, especially when the Moon's declination is large.

This second component involves the actual daily rate of motion of the Moon in right ascension. The influences of (a) a closer approach of the Moon to the Earth at perigee-syzygy, with a resulting larger parallax and faster lunar motion and (b) a large lunar declination, will always be reflected in a correspondingly high value of $\Delta\omega_2$-*S*. As in the case of $\Delta\omega_1$-*S*, therefore, a higher value of $\Delta\omega_2$-*S* indicates the presence of factors productive of enhanced tide-raising forces. As will be seen on following pages, the two components $\Delta\omega_1$-*S* and $\Delta\omega_2$-*S* are added (with proportionately far less emphasis on $\Delta\omega_2$-*S*) to obtain the most meaningful astronomical coefficient of tidal flooding potential.

Supplementary Note:

The effect of the Moon's greater tide-raising action when the Moon and Sun are both on the celestial equator is also worthy of attention. Although the Moon passes through 0° declination twice each lunar month in the same manner that it reaches a position of maximum (positive and negative) declination twice a month, very few of the 100 cases of tidal flooding enumerated in table 1 took place with the Moon on or very near the celestial equator. Many examples of tidal flooding have occurred with the Moon at or near its position of greatest declination.

The Sun is on the celestial equator only twice each year, at the vernal and autumnal equinoxes. Thus, the possibility for a combination of solar and lunar gravitational forces exactly in this plane occurs only 2 times a year—with the chance for coplanar alignment existing at either new moon or full moon. This small number of possible occurrences of reinforcing coplanar lunisolar tidal forces at 0° declination must be compared with the far greater frequency of cases of augmented lunar motion in right ascension when the Moon is at a high declination (e.g., $>\pm 18°$, approximately). Above this declination, a graph of declination as the ordinate versus right ascension (or time) as the abscissa recurves more rapidly toward the horizontal (figs. 44a, b), indicating a proportionately larger component of motion in α.

The latter motion creates the necessity for a corresponding catch-up motion by the rotating Earth, and results in a longer interval of amplified gravitational force action if the high lunar declination is coincident with perigee-syzygy.

The greater number of cases of such coplanar forces occurring at larger lunar declinations (up to $\pm 28.5°$) compared with those occurring at or very near declination 0° likewise increases the statistical probability for coincidence of these high declination cases with meteorological conditions of strong, onshore winds contributory to tidal flooding. It has been amply demonstrated in table 13, and can be even more fully corroborated by an analysis of table 16, that by far the greater number of cases of a large lunar parallax occur with the Moon at a relatively large declination—especially when the Moon is also coplanar with the Sun. The resulting closer approach of the Moon to the Earth (with the accompanying tide-raising force increasing inversely as the *cube* of the distance) caused by the orbital perturbations becomes of considerable significance. The coincidence of the Moon and Sun on the celestial equator cannot occur at solar perigee (i.e., perihelion) because the Sun is then near its maximum negative declination.

It is less cogent that the Moon's presence on the celestial equator is manifest in a reduction of its apparent angular velocity in right ascension (i.e., in the value of $\dot{\alpha}_{☾}$) by about $2°–4°/^d$ compared with the value of $\dot{\alpha}_{☾}$ when the Moon is at or near its maximum declinations of $\pm 23.5°$ to $\pm 28.5°$. Because of the weighted reduction formula for the total $\Delta\omega$-*S* coefficient, this relatively small decrease in the value of $\dot{\alpha}_{☾}$ is more than offset a the time of a close perigee-syzygy alignment by the corresponding increase in the angular velocity of both the Moon and perigee and the consequent larger value of $\Delta\omega_1$.

3. Evaluation of the $\Delta\omega$-S Coefficient

In the computational procedure for determining the numerical equivalent of $\Delta\omega$-*S*, the values of the angular rate of motion of the Moon with respect to perigee at the respective instants of perigee and syzygy must first be obtained. These two values can readily be established as a computer output by use of a Fortran formulation of the equation given in paragraph 3 of table 16B (p. 225).

Since the angular separation in longitude of the Moon from perigee is defined as the *true anomaly*, $v_{☾} = \nu_{☾} - \varpi_{☾}$, it only becomes necessary to differentiate the algorithmic expression for true anomaly in the form of a series expansion to determine its time rate of variation $\dot{\nu}_{☾}$. The resulting quantity may then be evaluated for any one instant of time without involving the individual differences between $\dot{\nu}_{☾}$, the rate of angular motion of the Moon, and $\dot{\varpi}_{☾}$ the rate of angular motion of perigee (both motions being expressed in $°/^d$, and both occurring in the plane of the lunar orbit).

It should be reiterated at this point that the single value of $\dot{\varpi}_{☾} = -1.6°/^d$ at perigee-syzygy, computed on page 180, is purely a representative figure for an average circumstance of perigee-syzygy, and is subject to considerable variation corresponding to different values of the separation-interval between these components. A basic tenet of the present evaluative procedure is, in fact, that the same variable solar forces which produce different amounts of perturbations in the lunar orbit also produce varying maxima in the height of the tides. It is upon this relationship that the use of these parameters in the astronomical portion of a coefficient of potential tidal flooding is based.

Since, vectorially, $\dot{v}_☾ = \dot{\nu}_☾ - \dot{\varpi}_☾$, in a graphic and analytic evaluation of $\dot{v}_☾$, the instantaneous angular velocity of the position of perigee (negative around the time the Moon reaches perigee) must be algebraically subtracted from the velocity of the Moon at this same time. The latter, direct motion is always positive. The vectorial sum thus yields an increased angular velocity of the Moon (still positive) *relative to perigee.*

The individual values of this relative velocity at the instants of (a) syzygy and (b) perigee are tabulated in columns 5 and 11, respectively, of table 16. Because a purely dimensionless coefficient is to be established, the units of angular velocity in $°/^{d}$ are dropped, permitting an otherwise incongruous combination of values possessing completely variant units in the several parts of the subsequent evaluating formula.

In determining the second component, $\Delta\omega_2$-S, the values of the instantaneous rate of change of the Moon's motion in right ascension (including the effects of declination) are computed by use of the expression for $\dot{\alpha}_☾$ given in paragraph 4 on page 226. These values, corresponding to the instants of syzygy and perigee, appear in the computer printout of table 16 in columns 6 and 12, respectively (the time units of right ascension being reduced, for consistency, to $°/^{d}$).

It is obvious that a further measure is necessary to establish the relatively greater importance assignable to the tide-raising *forces* resulting from the close lunar proximity to the Earth at perigee-syzygy (indicated by $\Delta\omega_1$-S) compared with the effect of the *prolongation* of these forces at the same time (indicated by $\Delta\omega_2$-S). The procedure used also serves to define a more explicit comparative influence of lunar proximity over the range between apogee-syzygy, perigee- or apogee-quadrature, perigee-syzygy, and proxigee-syzygy. It further maintains an appropriate relative perspective between astronomical contributions to tidal flooding and the hydrological and meteorological factors which follow. From empirical considerations, the data of columns 5 and 11 are multiplied by 4, with those of columns 6 and 12 being left the same.

The total expression for the $\Delta\omega$-S coefficient then becomes:

$$\Delta\omega\text{-}S = 4\dot{v}_☾ + \dot{\alpha}_☾$$

The sum of these two terms will subsequently become the astronomical portion of a multiparameter empirical formula applicable to the evaluation of tidal flooding potential—which includes the effects of local harmonic constituents, tidal range, and various meteorological circumstances as well.

Establishment of a Combined Astronomical-Meteorological Index to Potential Tidal Flooding

The speed of the wind, its direction, and duration of overwater movement are, of course, further aspects of importance in the production of tidal flooding. Strong winds, onshore winds, and those with a long *fetch*—or total distance of airflow over the sea surface—are all contributing factors to coastal flooding when added to astronomically amplified tidal conditions. Offshore winds provide a negative or subtractive effect. Low pressure atmospheric systems create an additional rise of water level by an amount equal to about 13 inches for each inch of barometric depression (i.e., approximately 1 centimeter per millibar), while high pressure systems cause a reduction in water level by the same amount. Meteorologically, therefore, a correction must also be applied to account for any deepening or filling of the overlying atmospheric pressure system during the 3-hour period since the preceding synoptic weather map.

With consideration to the foregoing and other factors, it is now possible to develop a single equation incorporating the various astronomical, meteorological, physical, and hydrographic elements which together serve to establish a greater or lesser potential for tidal flooding. Specifically, these elements include: (1) the effect of a perigee-syzygy alignment in increasing the tide-raising forces present, represented by the $\Delta\omega$-syzygy coefficient; (2) the response of the local tide to the semidiurnal lunar influence, which is that most prominent in connection with perigean spring tides, and here expressed for mathematical convenience by the term $M_2 - 1$; (3) the value of the mean spring (or diurnal) range of the tides at the place under consideration, representing a further aspect of local dynamic response to astronomical tide-producing influences, and incorporating as well a quantitative indication of the degree of constriction of tidal estuaries, shallowing of the ocean floor, and other variables; (4) the average velocity of the strong (usually >25 knots), persistent, and directionally steady wind movement over the sea surface necessary to support tidal flooding. The effects of the wind action on the sea surface are manifest in waves produced in the shallow waters immediately adjacent to the coastline, but may also persist in the form of swell hundreds of miles from the coastline (the total distance of such uninterrupted wind movement is known as the *fetch*); (5) the angle-of-attack of this overwater wind movement with respect to the shoreline, measured by the angle θ between the direction *from which* the wind is blowing and a normal or orthogonal line to that immediate section of coastline under consideration; (6) the duration of the overwater wind movement, expressed as a time factor [a] rather than in terms of distance, as in the case of the fetch; and (7) the atmospheric pressure gradient during the past 3 hours.

Thus, where:

Π = a combined astronomical-meteorological coefficient of potential tidal flooding (the capitalized symbol is derived from the first letter of the Greek word πλήμμρα meaning "flood-tide" or "inundation," and should not be confused with the lower-case symbol π universally used for astronomical parallax throughout this volume). (As a numerical index only, Π is dimensionless.)

$\dot{v}_{☾}$ = the rate of angular change in the Moon's true anomaly at the instant of syzygy (or perigee) (Vectorially, $\dot{v}_{☾} = \dot{\nu}_{☾} - \dot{\varpi}_{☾}$. The units of all three quantities are °/^{d}.)

$\dot{\nu}_{☾}$ = the rate of angular motion of the Moon in its orbit

$\dot{\varpi}_{☾}$ = the rate of angular motion of the lunar perigee along the orbit

$\dot{\alpha}_{☾}$ = the rate of lunar angular motion in right ascension (i.e., as projected on the celestial equator) at the instant of syzygy (or perigee)

$\Delta\omega\text{-}S = 4\dot{v}_{☾} + \dot{\alpha}_{☾}$

M_2 = the principal lunar semidiurnal component of the tides at the location under consideration (in feet)

$\bar{R}_s$ = the mean spring (or diurnal) tidal range at the same local station (in feet)

V = the mean velocity of the surface wind during at least a 3-hour period at a nearby reference coastal weather station (in knots)

θ = the angle measured between an axis extended to seaward perpendicular to the general coastline and the direction from which the wind is blowing (in degrees of arc)

D = the duration of a strong, sustained, onshore windflow over the body of water lying directly seaward (but with no limit on its total outward extent) from the coastal station (in hours)

ΔP = the change in barometric pressure at the coastal weather station, during the past 3 hours (in millibars)

A meaningful index quantifier describing the active potential for coastal flooding resulting from the combination of astronomical and meteorological causes may be represented by:

$$\Pi = \Delta\omega\text{-}S + (M_2 - 1) + \left(\frac{\bar{R}_s}{3.5} - 1\right) + V\cos\theta + D - 34\,(\pm\Delta P)$$

The final coefficient, 34 millibars, is approximately equivalent to an atmospheric pressure change of 1 inch of mercury—that required to raise or lower the water level by 1 foot. For simplification, the small effect of a rapidly moving atmospheric pressure system in itself altering the level of the sea surface is ignored in the above equation. The remaining numerical constants are arbitrary ones, based both upon empirical data and analytic convenience in establishing an average index value centered around 100.

The units in which the individual functions comprising this equation are customarily derived are specified in the preceding legend, but are not carried into the computations associated with this formula. Since the index is itself dimensionless and constitutes a purely relative measure, the various components of the equation may be safely combined, with their different units being ignored.

In this equation, it will be seen that the first term on the right—that expressing the effect of a perigee-syzygy alignment—is always positive. So also, in successive order are M_2, $\bar{R}_s$, and V, the magnitude of the wind velocity. The cosine function in the fourth term automatically takes care of the tide-raising or tide-reducing effects created by onshore or offshore components of the wind, respectively. The corresponding additive or subtractive functions are indicated by the algebraic sign customarily assigned to this trigonometric function in the quadrant concerned. The value of D is again always positive, but the algebraic sign of the last term varies respectively from plus to minus with rise or fall in atmospheric pressure (the corresponding correction being taken care of by the minus sign in front of the parentheses).

The greater the amount by which the numerical value of this index is in excess of 100 (representing an average

[a] The reason for use of the dimensional unit of time rather than distance is obvious when an actual example such as the great mid-Atlantic tidal flooding of 1962 is considered. Because of stagnation of the offshore low pressure center, the distance of overwater wind movement remained relatively constant. However, the onshore windflow persisted timewise through 2.5 days and 5 successive high tides, during each of which continuously height-accelerating effects were felt.

condition) the greater is the potential for tidal flooding. Examples demonstrating the application of this index to the determination of tidal flooding potential, and showing in the relative magnitude of Π a very close agreement with the severity of the flooding conditions actually encountered are given in table 30. These and other desired historical examples for which Π has been evaluated may be compared with the extent of tidal flooding described for specific cases in chapter 7 and in the newspaper accounts comprising table 5 of part I, chapter 1.

This index to potential tidal flooding is presently in an analytic stage of development and largely dependent upon correlations with empirical data. Appropriate adjustments within the individual portions of the formula will undoubtedly occur as additional comparisons are made with future coastal flooding events. With this understanding, the expression for Π is to be regarded as a provisional one, pending the realization of such a definitive indicator.

The incorporation of the various contributing causes to tidal flooding in such a single numerical index is intended principally to achieve a generalized descriptor term leading toward an awareness of the increased tidal flooding potential occasioned by tide-amplifying astronomical conditions, where supporting meteorological conditions are also present. In connection with meteorological investigations of hurricanes and storm surges, N. Arthur Pore, Chester P. Jelesnianski, and others (see bibliography—category 18) have derived various theoretical, empirical, and modular formulae for predicting the height of waves, wave setup conditions, swell, and storm surges under conditions of strong, onshore winds. These formulae are based upon such factors as wind stress vectors, offshore surface-pressure fields, maximum storm winds, and the magnitudes and distributions of these and related meteorological elements within rectangular grid systems covering the coastal waters. Such formulae will prove more satisfactory for detailed analytical evaluations, bearing in mind an earlier clarification that a storm surge analyzed for meteorological purposes does not necessarily imply coastal flooding potential.

The numerical evaluation of Π is designed to provide an expedient and, where appropriate, a timely forewarning of astronomical tidal flooding potential should critical meteorological conditions also prevail. A more comprehensive evaluation is achieved when most of the terms in the expression are employed. However, where certain elements are lacking—or in the exigencies of the moment—a partial indication of any pending tidal flooding threat to the shoreline may be secured by the combined utilization (or separate analysis of) all parameters in the equation which are immediately available.

TABLE 30.—*Examples Involving the Use of the Δω-S Coefficient in Establishing a Combined Astronomical-Meteorological Index* (Π) *of Potential Tidal Flooding*

The astronomical coefficients are computed for the mean epochs of perigee- (proxigee-) syzygy and are combined with the most representative meteorological data available for the cases evaluated.*

Key No.	Date; flooding location (or that of the nearest tide station)	Astronomical-Tidal Parameters			Meteorological Parameters			Potential for tidal flooding	
		Δω-*S* coefficient (table 16)	M_2-1 (table 19)	$\frac{\overline{R}_s}{3.5}-1$ (table 19)	$V\cos\theta$ (kt)	*D* (h)	34 (±*P*)	Index Π	Intensity rating
D–57	1931, Mar. 4–5, New York (The Battery), N.Y.	82. 178	1. 138	0. 5	52	36	....	171. 8	Extreme.
F–68	1939, Jan. 3–5, Aberdeen, Wash.	84. 056	2. 425	. 9	43	48	....	168. 4	Severe.
I–83e	1959, Dec. 29, Boston, Mass.....	84. 105	3. 422	3. 1	56	20	....	166. 6	Severe.
J–85	1962, Mar. 6–7, Entire mid-Atlantic coast (Breakwater Harbor, Del.).	83. 025	. 916	. 4	30	65	....	179. 3	Extreme.
N–99	1974, Jan. 8, Malibu Beach (Los Angeles, Calif.).	84. 611	. 695	. 5	35	24	....	144. 8	Strong.
	(Willets Point, N.Y.)..........	84. 611	2. 619	1. 4	−8	0	....	80. 6	Insignificant.
O–100	1976, Mar. 17, Halifax, Nova Scotia.	82. 371	1. 046	. 5	43	10	....	136. 9	Moderate.

Intensity rating scale:

$\Pi \geq 170$—Extreme.	$\Pi \geq 120$—Moderate.
$\Pi \geq 160$—Severe.	$\Pi \geq 100$—Slight.
$\Pi \geq 140$—Strong.	$\Pi < 100$—Insignificant.

**Note:* Precise values for the rates of barometric pressure change in the past 3 hours at local stations are best obtained from original hourly weather data in each case and, accordingly, have not been inserted in the above table.

One further requirement for extensive tidal flooding is, of course, the involvement of a lowlying coastal area, whose mean elevation is only some few feet above the level of mean high water spring tides, and in which any upward slope (positive gradient) extending inland from the sea is also small.

Empirical Support for the Validity of the Delta Omega-Syzygy Coefficient Provided by Predicted and Observed Tidal Height Data

Comprising the next step in an evaluative process to determine the reliability of the Δω-syzygy coefficient as one factor in a multiple-parameter indicator of tidal flooding potential, it is desirable to subject this coefficient to appropriate quantitative tests. In this process, certain cases of perigee-syzygy alignment possessing unusually high Δω-syzygy coefficients computed directly from the data in table 16 are compared with predicted tidal data for the same dates contained within official government tide tables. Dates on which tidal flooding has been observed to occur are selected for such analyses.

In this comparison with examples of known tidal flooding, the objective is that of discovering all consistent relationships between the Δω-syzygy coefficient and predicted or observed tide data which either give support to, or contradict, the interpretations made from the previously considered, purely astronomical data.

A necessary preliminary to the establishment of factors of correlation between the astronomically related Δω-syzygy coefficient and corresponding tidal data is the discovery of a suitable common-response parameter. A study of the individual items published in tide tables giving the times and heights of the tides reveals that no one of the quantities published is, in its present form, directly suitable for the desired correlations. However, through additional analysis, several of these can be made useful in this regard.

The above-average water levels predicted for the times of perigean spring tides are, of course, a clear indication that increased gravitational tide-raising forces are active at these times. However, when the values of tide height close to perigee-syzygy are compared with those occurring in certain cases of unusual uplift produced by other than perigee-syzygy conditions, the high waters predicted for these latter cases may, in some instances, be equal to, or sometimes even greater than, those predicted for perigean spring tides. For reasons which will later be shown, predicted tide height alone is not, therefore, a totally reliable indicator of tidal flooding potential.

Among such predicted tidal data, a second practical indicator of perigean spring tides exists in the large daily ranges usually displayed by this type of tide (with certain exceptions listed under "Diurnal Tides" in table 19). The maximum daily tidal range is obtained as the simple difference between the height of higher high water and the immediately preceding or succeeding lower low water. Again, however, the tidal range is closely affected by the diurnal inequality, a lunar declinational influence whose observed effects are more commonly associated with the tides of the Pacific Ocean than those of the east coast of North America (except for Atlantic coast locations at high latitudes).

Some other more consistent parameter available from tide tables which is indicative of the relative tidal flooding potential of perigean spring tides when these are reinforced by appropriate meteorological conditions is obviously needed.

The Lengthened Tidal Day as an Indicator of Increased Tidal Flooding Potential

Such an indirect indication of tidal flooding potential is obtainable through the analysis of the predicted *times* of higher high waters. A consideration of the daily differences between these times of higher high water provides a valuable corroboration for the validity of the purely astronomically derived Δω-syzygy coefficient. This temporal relation also provides support to an emphasis given earlier to the increased length of the tidal day as an important adjunct of perigean spring tides.

In the columns of tide tables immediately to the left of those indicating the predicted heights of high and low waters, the times of the highest high water in each day (specified in hours and minutes) can be found. If the time opposite the highest high water for each day is subtracted (with proper attention to the sexagesimal system used in timekeeping) from the corresponding value for the following day, the desired difference in time between consecutive higher high waters is obtained.

This interval will always be slightly more than 24 hours, and represents the length of the *tidal day* which, although not precisely the same in its possible range of values, is directly related to the *lunar day,* defined as the period of time between two successive upper transits of the Moon across the local meridian of any place.

Tables 31a,b,c,d and figs. 152a,b, applicable to Breakwater Harbor, Del., illustrate the graphical procedure used in determining the effect of the lengthened lunar day upon perigean spring tides. This effect is additive to that of the increased gravitational forces of the Moon

TABLE 31a, b, c, d.—*Data Used in Evaluating the Increased Length of the Tidal Day at Perigee-Syzygy (Made Comparatively More Effective by the Greater Gravitational Force at These Times) as Plotted on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

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Times and Heights of High and Low Waters

JANUARY

Day	Time h. m.	Ht. ft.
M 1	0359	3.8
	1005	0.6
	1612	3.5
	2217	0.2
51		
T 2	0450	4.1
	1102	0.4
	1704	3.5
	2304	0.0
48		
W 3	0538	4.4
	1155	0.2
	1755	3.6
	2352	-0.2
47		
T 4	0625	4.8
	1245	0.0
	1843	3.7
47		
F 5	0039	-0.4
	0712	5.0
	1333	-0.2
	1932	3.8
47		
S 6 **S**	0127	-0.5
	0759	5.3
	1421	-0.4
	2020	4.0
47		
S 7 **NM**	0215	-0.6
	0846	5.4
	1510	-0.5
	2109	4.0
48		
M 8	0305	-0.7
	0934	5.4
	1600	-0.6
	2200	4.1
50		
T 9 **P**	0358	-0.6
	1024	5.3
	1649	-0.5
	2253	4.1
53		
W10	0451	-0.5
	1117	5.0
	1741	-0.4
	2349	4.1
56		
T11	0548	-0.2
	1213	4.7
	1834	-0.3
58		
F12 **E**	0050	4.1
	0651	0.0
	1311	4.4
	1931	-0.2
62		
S13 **FQ**	0152	4.1
	0758	0.2
	1414	4.0
	2029	-0.1
66		
S14	0258	4.2
	0908	0.3
	1520	3.8
	2128	0.0
65		
M15	0403	4.3
	1018	0.3
	1626	3.6
	2225	0.1
61		

Day	Time h. m.	Ht. ft.
T16	0504	4.4
	1124	0.3
	1727	3.6
	2320	0.1
56		
W17	0600	4.6
	1222	0.2
	1822	3.5
49		
T18	0010	0.1
	0649	4.7
	1312	0.1
	1911	3.6
44		
F19 **N**	0057	0.0
	0733	4.7
	1355	0.1
	1954	3.6
41		
S20	0139	0.0
	0814	4.7
	1434	0.1
	2034	3.6
38		
S21 **FM**	0220	0.0
	0852	4.7
	1511	0.1
	2111	3.6
37		
M22	0300	0.0
	0929	4.6
	1547	0.1
	2148	3.6
36		
T23	0339	0.1
	1005	4.5
	1623	0.1
	2225	3.6
38		
W24	0419	0.1
	1043	4.3
	1700	0.2
	2304	3.6
38		
T25 **A**	0501	0.3
	1121	4.1
	1738	0.3
	2344	3.6
41		
F26	0545	0.4
	1202	3.9
	1818	0.3
44		
S27 **E**	0030	3.6
	0633	0.5
	1246	3.7
	1901	0.4
48		
S28	0118	3.7
	0726	0.6
	1334	3.5
	1949	0.4
54		
M29 **LQ**	0212	3.8
	0824	0.7
	1429	3.4
	2040	0.4
57		
T30	0309	3.9
	0925	0.6
	1527	3.3
	2134	0.3
58		
W31	0407	4.2
	1026	0.5
	1627	3.4
	2228	0.1
57		

FEBRUARY

Day	Time h. m.	Ht. ft.
T 1	0504	4.5
	1125	0.2
	1725	3.5
	2323	-0.2
54		
F 2	0558	4.8
	1220	0.0
	1820	3.7
52		
S 3 **S**	0016	-0.4
	0650	5.1
	1312	-0.3
	1913	4.0
51		
S 4	0109	-0.6
	0741	5.3
	1402	-0.5
	2003	4.2
49		
M 5 **NM**	0201	-0.8
	0830	5.5
	1451	-0.7
	2054	4.4
49		
T 6 **P**	0254	-0.9
	0919	5.4
	1539	-0.8
	2144	4.5
50		
W 7	0346	-0.8
	1009	5.3
	1627	-0.7
	2236	4.6
52		
T 8	0439	-0.7
	1101	5.0
	1716	-0.6
	2330	4.6
53		
F 9 **E**	0535	-0.4
	1154	4.6
	1806	-0.4
56		
S10	0026	4.4
	0634	-0.2
	1250	4.2
	1900	-0.2
60		
S11	0126	4.3
	0738	0.1
	1351	3.8
	1958	0.1
65		
M12 **FQ**	0231	4.2
	0847	0.3
	1458	3.5
	2059	0.2
67		
T13	0338	4.2
	0959	0.4
	1607	3.4
	2201	0.3
65		
W14	0443	4.2
	1107	0.4
	1712	3.3
	2301	0.3
58		
T15 **N**	0541	4.3
	1205	0.4
	1807	3.4
	2355	0.3
50		

Day	Time h. m.	Ht. ft.
F16	0631	4.4
	1253	0.3
	1855	3.5
44		
S17	0041	0.2
	0715	4.4
	1333	0.2
	1936	3.6
39		
S18	0123	0.1
	0754	4.5
	1408	0.1
	2012	3.7
36		
M19	0202	0.0
	0830	4.5
	1443	0.1
	2046	3.8
34		
T20 **FM**	0239	0.0
	0904	4.4
	1516	0.1
	2120	3.9
34		
W21 **A**	0317	0.0
	0938	4.3
	1548	0.1
	2154	3.9
35		
T22	0355	0.0
	1013	4.2
	1622	0.1
	2229	4.0
36		
F23 **E**	0434	0.1
	1049	4.1
	1657	0.2
	2307	4.0
37		
S24	0515	0.2
	1126	3.9
	1735	0.2
	2348	3.9
41		
S25	0600	0.3
	1207	3.6
	1817	0.3
47		
M26	0034	3.9
	0650	0.4
	1254	3.4
	1904	0.3
52		
T27	0126	3.9
	0747	0.5
	1349	3.3
	1958	0.4
60		
W28 **LQ**	0226	4.0
	0850	0.5
	1451	3.2
	2056	0.3
64		

MARCH

Day	Time h. m.	Ht. ft.
T 1	0330	4.2
	0954	0.4
	1558	3.3
	2158	0.1
63		
F 2 **S**	0433	4.4
	1057	0.2
	1701	3.5
	2300	-0.1
60		
S 3	0533	4.7
	1155	-0.1
	1800	3.9
	2359	-0.4
56		
S 4	0629	5.0
	1248	-0.4
	1854	4.2
53		
M 5	0054	-0.7
	0722	5.2
	1338	-0.6
	1947	4.5
51		
T 6 **P NM**	0148	-0.9
	0813	5.3
	1427	-0.8
	2036	4.8
49		
W 7	0241	-1.0
	0902	5.3
	1514	-0.9
	2126	5.0
49		
T 8 **E**	0333	-1.0
	0951	5.1
	1602	-0.8
	2215	5.0
50		
F 9	0425	-0.8
	1041	4.8
	1649	-0.6
	2307	4.9
52		
S10	0519	-0.5
	1133	4.4
	1738	-0.4
55		
S11	0001	4.7
	0615	-0.2
	1228	4.0
	1829	-0.1
57		
M12	0058	4.4
	0716	0.1
	1328	3.6
	1927	0.2
62		
T13 **FQ**	0200	4.2
	0822	0.4
	1435	3.3
	2029	0.5
67		
W14	0307	4.1
	0933	0.5
	1546	3.2
	2134	0.6
67		
T15 **N**	0414	4.0
	1041	0.5
	1652	3.2
	2238	0.6
61		

Day	Time h. m.	Ht. ft.
F16	0515	4.0
	1138	0.5
	1747	3.4
	2334	0.5
50		
S17	0605	4.1
	1223	0.4
	1832	3.5
44		
S18	0021	0.3
	0649	4.2
	1301	0.3
	1910	3.7
39		
M19	0102	0.2
	0728	4.2
	1334	0.2
	1945	3.9
34		
T20 **A**	0140	0.0
	0802	4.3
	1407	0.1
	2017	4.0
34		
W21 **FM VE**	0217	-0.1
	0836	4.3
	1439	0.0
	2050	4.2
33		
T22 **E**	0254	-0.1
	0909	4.2
	1511	0.0
	2123	4.2
35		
F23	0331	-0.1
	0943	4.1
	1545	0.0
	2158	4.3
36		
S24	0409	-0.1
	1018	3.9
	1620	0.1
	2234	4.3
40		
S25	0450	0.0
	1056	3.7
	1658	0.1
	2314	4.3
41		
M26	0534	0.1
	1137	3.5
	1740	0.2
48		
T27	0000	4.2
	0623	0.3
	1225	3.3
	1828	0.3
52		
W28	0052	4.2
	0720	0.4
	1321	3.2
	1925	0.4
60		
T29 **LQ S**	0152	4.1
	0822	0.4
	1426	3.2
	2028	0.3
67		
F30	0259	4.2
	0928	0.3
	1535	3.4
	2135	0.2
67		
S31	0406	4.4
	1030	0.1
	1641	3.7
	2241	0.0
64		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 31a, b, c, d.—*Data Used in Evaluating the Increased Length of the Tidal Day at Perigee-Syzygy (Made Comparatively More Effective by the Greater Gravitational Force at These Times) as Plotted on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

BREAKWATER HARBOR, DEL., 1962 75

Times and Heights of High and Low Waters

APRIL

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
S 1	0510 1129 1741 2343	4.6 -0.2 4.1 -0.4	M16 **A**	0613 1218 1836	3.9 0.3 3.9
57 M 2	0607 1222 1836	4.8 -0.5 4.5	**35** T17	0036 0652 1253 1911	0.2 4.0 0.2 4.1
55 T 3	0041 0702 1312 1928	-0.7 5.0 -0.7 4.9	**35** W18 **E**	0114 0729 1327 1946	0.1 4.0 0.1 4.3
51 W 4 **P E**	0135 0753 1400 2017	-0.9 5.0 -0.9 5.2	**33** T19	0152 0803 1401 2019	-0.1 4.0 0.0 4.4
49 T 5 **NM**	0227 0842 1447 2106	-1.0 5.0 -0.9 5.3	**35** F20 **FM**	0229 0838 1435 2054	-0.2 4.0 0.0 4.5
48 F 6	0319 0931 1534 2154	-0.9 4.7 -0.8 5.2	**35** S21	0307 0914 1510 2129	-0.2 3.9 0.0 4.6
49 S 7	0410 1021 1621 2243	-0.8 4.5 -0.5 5.1	**37** S22	0347 0950 1547 2206	-0.2 3.7 0.0 4.6
52 S 8	0502 1112 1708 2335	-0.5 4.1 -0.2 4.8	**42** M23	0429 1030 1627 2248	-0.1 3.6 0.1 4.5
– M 9	0555 1206 1800	-0.2 3.7 0.1	**47** T24	0515 1114 1712 2335	0.0 3.5 0.2 4.5
54 T10	0029 0653 1306 1855	4.5 0.1 3.4 0.4	**–** W25	0604 1204 1803	0.1 3.3 0.3
58 W11 **N**	0127 0755 1411 1956	4.2 0.4 3.2 0.6	**54** T26 **S**	0029 0701 1303 1902	4.4 0.2 3.3 0.3
64 T12 **FQ**	0231 0901 1520 2102	4.0 0.5 3.2 0.8	**60** F27	0129 0801 1409 2008	4.3 0.2 3.4 0.3
66 F13	0337 1002 1622 2206	3.8 0.5 3.3 0.7	**66** S28 **LQ**	0235 0904 1518 2118	4.3 0.1 3.6 0.2
60 S14	0437 1056 1714 2304	3.8 0.5 3.4 0.6	**68** S29	0343 1004 1623 2225	4.3 -0.1 3.9 0.0
51 S15	0528 1140 1759 2354	3.9 0.4 3.7 0.4	**63** M30	0446 1102 1723 2328	4.4 -0.3 4.4 -0.3
45			**55**		

MAY

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
T 1	0545 1155 1818	4.5 -0.5 4.8	W16 **E**	0001 0610 1207 1835	0.3 3.7 0.2 4.2
51 W 2 **E P**	0027 0640 1245 1909	-0.5 4.6 -0.7 5.1	**37** T17	0043 0650 1245 1912	0.1 3.8 0.1 4.5
50 T 3	0121 0732 1333 1959	-0.7 4.6 -0.8 5.3	**36** F18	0124 0729 1322 1948	0.0 3.8 0.0 4.6
47 F 4 **NM**	0213 0822 1420 2046	-0.8 4.5 -0.7 5.4	**37** S19	0203 0807 1400 2025	-0.1 3.7 -0.1 4.8
47 S 5	0304 0911 1507 2133	-0.8 4.3 -0.6 5.3	**38** S20 **FM**	0245 0846 1438 2103	-0.2 3.7 -0.1 4.9
47 S 6	0354 1001 1553 2220	-0.6 4.1 -0.4 5.1	**41** M21	0327 0926 1520 2144	-0.2 3.6 -0.1 4.9
48 M 7	0444 1051 1641 2308	-0.4 3.8 -0.1 4.8	**44** T22	0412 1009 1603 2228	-0.2 3.5 0.0 4.8
– T 8 **N**	0535 1144 1730	-0.2 3.5 0.2	**49** W23 **S**	0459 1058 1652 2317	-0.1 3.5 0.0 4.7
52 W 9	0000 0627 1240 1824	4.5 0.1 3.3 0.5	**–** T24	0549 1151 1746	-0.1 3.5 0.2
54 T10	0054 0723 1340 1923	4.2 0.3 3.2 0.7	**54** F25	0011 0643 1250 1847	4.6 0.0 3.5 0.2
58 F11	0152 0819 1442 2026	3.9 0.4 3.2 0.8	**59** S26	0110 0741 1355 1954	4.4 0.0 3.6 0.3
59 S12 **FQ**	0251 0914 1540 2129	3.7 0.5 3.3 0.8	**64** S27 **LQ**	0214 0840 1502 2103	4.3 -0.1 3.9 0.2
58 S13	0349 1003 1632 2225	3.7 0.5 3.5 0.7	**66** M28	0320 0939 1605 2210	4.2 -0.2 4.2 0.1
45 M14 **A**	0441 1049 1717 2316	3.7 0.4 3.8 0.5	**57** T29 **E**	0424 1035 1704 2314	4.2 -0.3 4.5 -0.1
41 T15	0528 1130 1758	3.7 0.3 4.0	**56** W30 **P**	0524 1128 1800	4.2 -0.4 4.9
37			**51** T31	0013 0620 1219 1851	-0.3 4.2 -0.5 5.1
			50		

JUNE

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
F 1	0108 0713 1307 1941	-0.5 4.1 -0.5 5.3	S16	0056 0655 1246 1919	0.1 3.6 -0.1 4.8
47 S 2	0200 0803 1355 2028	-0.5 4.1 -0.5 5.3	**42** S17	0139 0738 1328 2001	-0.1 3.6 -0.2 5.0
45 S 3 **NM**	0250 0853 1442 2113	-0.5 3.9 -0.4 5.2	**42** M18 **FM**	0223 0821 1412 2043	-0.2 3.6 -0.3 5.1
45 M 4	0338 0941 1528 2158	-0.4 3.8 -0.2 5.0	**44** T19 **S**	0308 0906 1459 2127	-0.3 3.7 -0.3 5.1
46 T 5 **N**	0424 1029 1615 2244	-0.3 3.6 0.1 4.7	**46** W20	0355 0953 1547 2213	-0.3 3.7 -0.2 5.0
47 W 6	0511 1119 1703 2331	-0.1 3.5 0.3 4.4	**50** T21	0442 1044 1639 2303	-0.3 3.7 -0.2 4.9
– T 7	0558 1209 1753	0.1 3.4 0.5	**54** F22 **SS**	0532 1138 1734 2357	-0.3 3.7 0.0 4.7
48 F 8	0019 0645 1303 1847	4.1 0.3 3.3 0.7	**–** S23	0624 1236 1835	-0.3 3.8 0.1
50 S 9	0109 0733 1356 1945	3.9 0.4 3.3 0.8	**57** S24 **P**	0054 0719 1338 1940	4.5 -0.2 3.9 0.2
53 S10 **FQ**	0202 0822 1450 2043	3.7 0.4 3.4 0.8	**61** M25 **LQ**	0155 0816 1443 2048	4.2 -0.2 4.1 0.2
53 M11 **A**	0255 0909 1541 2140	3.6 0.4 3.6 0.7	**65** T26 **E**	0300 0913 1546 2157	4.1 -0.2 4.4 0.1
48 T12 **E**	0349 0956 1629 2233	3.5 0.3 3.8 0.6	**61** W27	0403 1009 1647 2302	3.9 -0.2 4.6 0.0
45 W13	0439 1040 1714 2323	3.5 0.3 4.1 0.4	**62** T28	0505 1104 1743	3.8 -0.3 4.8
43 T14	0526 1123 1757	3.5 0.2 4.3	**52** F29	0003 0603 1157 1835	-0.1 3.8 -0.3 5.0
41 F15	0010 0611 1204 1838	0.2 3.5 0.0 4.6	**50** S30	0058 0658 1247 1925	-0.2 3.8 -0.3 5.1
41			**46**		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 31a, b, c, d.—*Data Used in Evaluating the Increased Length of the Tidal Day at Perigee-Syzygy (Made Comparatively More Effective by the Greater Gravitational Force at These Times) as Plotted on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

76 **BREAKWATER HARBOR, DEL., 1962**

Times and Heights of High and Low Waters

JULY

Day	Time h. m.	Ht. ft.
S 1	0148	-0.3
	0749	3.7
	1334	-0.2
	2011	5.1
44		
M 2	0235	-0.3
NM	0836	3.7
	1421	-0.2
N	2055	5.0
42		
T 3	0319	-0.2
	0921	3.6
	1506	0.0
	2137	4.8
41		
W 4	0402	-0.1
	1004	3.6
	1551	0.1
	2218	4.6
43		
T 5	0442	0.0
	1049	3.5
	1636	0.2
	2301	4.4
42		
F 6	0523	0.1
	1134	3.5
	1722	0.4
	2343	4.1.
–		
S 7	0603	0.2
	1219	3.5
	1810	0.5
45		
S 8	0028	3.9
A	0646	0.3
	1307	3.5
	1902	0.7
47		
M 9	0115	3.7
E	0731	0.3
	1356	3.6
	1957	0.7
48		
T10	0203	3.5
FQ	0817	0.4
	1448	3.7
	2054	0.7
52		
W11	0257	3.4
	0904	0.3
	1540	3.9
	2150	0.7
56		
T12	0351	3.3
	0952	0.3
	1630	4.1
	2245	0.5
49		
F13	0443	3.3
	1040	0.2
	1719	4.3
	2337	0.3
45		
S14	0534	3.4
	1128	0.0
	1804	4.6
48		
S15	0027	0.1
	0623	3.5
	1216	-0.1
	1852	4.9
46		

Day	Time h. m.	Ht. ft.
M16	0115	-0.1
	0711	3.6
	1303	-0.3
	1938	5.1
46		
T17	0201	-0.3
S	0759	3.7
	1352	-0.4
FM	2024	5.2
46		
W18	0247	-0.4
	0847	3.9
	1442	-0.5
	2110	5.3
48		
T19	0334	-0.5
	0936	4.0
	1533	-0.5
	2158	5.2
50		
F20	0421	-0.6
P	1027	4.1
	1626	-0.4
	2248	5.0
52		
S21	0510	-0.5
	1121	4.2
	1722	-0.3
	2340	4.7
–		
S22	0601	-0.4
	1218	4.2
	1821	-0.1
57		
M23	0037	4.4
E	0654	-0.3
	1318	4.3
	1925	0.1
59		
T24	0136	4.1
LQ	0750	-0.2
	1421	4.3
	2033	0.2
65		
W25	0240	3.8
	0848	-0.1
	1526	4.4
	2143	0.2
63		
T26	0346	3.6
	0946	0.0
	1629	4.5
	2251	0.2
59		
F27	0452	3.5
	1045	0.0
	1728	4.7
	2353	0.1
54		
S28	0552	3.5
	1140	0.0
	1822	4.8
49		
S29	0047	0.0
N	0646	3.5
	1232	0.0
	1911	4.8
44		
M30	0134	0.0
	0735	3.6
	1319	0.0
	1955	4.8
41		
T31	0216	-0.1
	0819	3.6
	1403	0.0
	2036	4.7
39		

AUGUST

Day	Time h. m.	Ht. ft.
W 1	0255	-0.1
NM	0859	3.7
	1446	0.0
	2114	4.6
38		
T 2	0332	0.0
	0937	3.7
	1528	0.1
	2152	4.5
37		
F 3	0408	0.0
	1015	3.7
	1609	0.2
	2229	4.3
38		
S 4	0444	0.1
	1054	3.7
	1651	0.2
	2307	4.1
40		
S 5	0521	0.2
A	1135	3.7
	1736	0.4
	2347	3.9
–		
M 6	0600	0.2
E	1218	3.7
	1823	0.5
43		
T 7	0030	3.6
	0642	0.3
	1305	3.7
	1914	0.6
53		
W 8	0117	3.4
	0727	0.4
	1357	3.8
	2010	0.7
54		
T 9	0208	3.3
FQ	0816	0.4
	1451	3.9
	2109	0.7
57		
F10	0305	3.2
	0908	0.3
	1548	4.1
	2207	0.6
55		
S11	0404	3.2
	1002	0.2
	1643	4.3
	2305	0.3
53		
S12	0502	3.3
	1058	0.1
	1736	4.6
	2359	0.1
51		
M13	0557	3.5
S	1151	-0.2
	1827	4.9
49		
T14	0049	-0.2
	0649	3.8
	1243	-0.4
	1916	5.1
48		
W15	0136	-0.4
	0739	4.0
	1335	-0.6
	2004	5.3
49		

Day	Time h. m.	Ht. ft.
T16	0223	-0.6
FM	0828	4.3
	1427	-0.7
	2053	5.3
47		
F17	0310	-0.8
P	0917	4.5
	1519	-0.8
	2140	5.2
50		
S18	0357	-0.8
	1007	4.6
	1613	-0.7
	2230	5.0
52		
S19	0445	-0.7
E	1100	4.6
	1708	-0.5
	2322	4.6
55		
M20	0534	-0.6
	1155	4.6
	1805	-0.2
60		
T21	0017	4.3
	0626	-0.3
	1255	4.5
	1908	0.0
63		
W22	0117	3.9
LQ	0722	-0.1
	1358	4.4
	2017	0.2
66		
T23	0222	3.6
	0822	0.1
	1504	4.4
	2129	0.3
68		
F24	0333	3.4
	0926	0.2
	1612	4.4
	2239	0.3
61		
S25	0441	3.3
	1029	0.3
	1713	4.4
	2340	0.2
53		
S26	0542	3.4
N	1128	0.2
	1806	4.5
48		
M27	0032	0.1
	0634	3.5
	1219	0.2
	1854	4.5
42		
T28	0114	0.1
	0718	3.6
	1304	0.1
	1936	4.5
37		
W29	0151	0.0
	0757	3.8
	1345	0.0
	2013	4.5
36		
T30	0225	0.0
NM	0832	3.9
	1425	0.0
	2049	4.4
34		
F31	0259	0.0
	0906	3.9
	1503	0.0
	2123	4.3
34		

SEPTEMBER

Day	Time h. m.	Ht. ft.
S 1	0331	0.0
	0941	4.0
	1542	0.0
	2157	4.2
35		
S 2	0403	0.0
A	1016	4.0
E	1622	0.1
	2232	4.0
38		
M 3	0439	0.1
	1054	4.0
	1703	0.2
	2309	3.7
41		
T 4	0516	0.2
	1135	4.0
	1748	0.4
	2350	3.5
45		
W 5	0556	0.3
	1220	3.9
	1837	0.5
50		
T 6	0036	3.3
	0642	0.4
	1310	3.9
	1933	0.6
56		
F 7	0129	3.1
FQ	0733	0.4
	1406	4.0
	2033	0.6
62		
S 8	0229	3.1
	0831	0.4
	1508	4.1
	2136	0.5
61		
S 9	0334	3.1
S	0931	0.3
	1609	4.3
	2235	0.3
58		
M10	0437	3.3
	1032	0.1
	1707	4.6
	2331	0.0
56		
T11	0534	3.7
	1130	-0.2
	1803	4.8
51		
W12	0023	-0.3
	0628	4.0
	1226	-0.5
	1854	5.1
50		
T13	0110	-0.6
	0718	4.4
	1319	-0.7
	1944	5.2
48		
F14	0157	-0.8
FM	0807	4.7
	1412	-0.9
	2032	5.2
49		
S15	0243	-0.9
P	0857	5.0
E	1504	-0.9
	2121	5.1
48		

Day	Time h. m.	Ht. ft.
S16	0330	-0.9
	0946	5.1
	1558	-0.8
	2209	4.8
52		
M17	0417	-0.8
	1038	5.0
	1652	-0.6
	2302	4.4
54		
T18	0506	-0.5
	1132	4.9
	1749	-0.3
	2357	4.0
58		
W19	0558	-0.2
	1230	4.7
	1850	0.0
63		
T20	0058	3.7
	0655	0.1
	1333	4.4
	1959	0.2
68		
F21	0205	3.4
LQ	0758	0.3
	1441	4.3
	2111	0.4
68		
S22	0319	3.2
N	0905	0.5
	1549	4.2
	2220	0.4
63		
S23	0429	3.3
	1012	0.5
	1652	4.2
	2319	0.3
53		
M24	0527	3.4
AE	1112	0.4
	1745	4.2
45		
T25	0005	0.2
	0614	3.6
	1203	0.3
	1830	4.2
40		
W26	0045	0.1
	0655	3.8
	1246	0.2
	1910	4.3
36		
T27	0119	0.1
	0730	3.9
	1325	0.1
	1946	4.3
36		
F28	0150	0.0
	0802	4.1
	1402	0.0
	2020	4.2
33		
S29	0221	0.0
NM E	0836	4.2
	1439	0.0
A	2053	4.1
32		
S30	0253	0.0
	0908	4.3
	1516	0.0
	2125	4.0
35		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 31a, b, c, d.—*Data Used in Evaluating the Increased Length of the Tidal Day at Perigee-Syzygy (Made Comparatively More Effective by the Greater Gravitational Force at These Times) as Plotted on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

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Times and Heights of High and Low Waters

OCTOBER

Day	Time (h. m.)	Ht. (ft.)	Day	Time (h. m.)	Ht. (ft.)
M 1	0326 0943 1555 2159	0.0 4.3 0.0 3.8	T16	0351 1016 1636 2242	-0.8 5.3 -0.6 4.2
35 T 2	0400 1018 1635 2236	0.1 4.3 0.1 3.6	52 W17	0439 1108 1732 2337	-0.5 5.0 -0.3 3.8
40 W 3	0437 1058 1719 2316	0.2 4.2 0.3 3.4	56 T18	0531 1204 1831	-0.1 4.7 0.0
44 T 4	0517 1142 1807	0.2 4.2 0.4	61 F19 N	0038 0627 1305 1936	3.5 0.2 4.4 0.2
50 F 5	0002 0602 1232 1902	3.2 0.4 4.1 0.5	66 S20 LQ	0146 0730 1411 2044	3.3 0.5 4.1 0.4
58 S 6	0057 0657 1330 2003	3.1 0.4 4.1 0.5	68 S21	0258 0838 1519 2148	3.2 0.7 4.0 0.4
64 S 7 S FQ	0200 0759 1434 2106	3.1 0.4 4.1 0.4	61 M22	0403 0946 1620 2244	3.3 0.7 3.9 0.4
65 M 8	0308 0904 1539 2206	3.2 0.3 4.3 0.2	53 T23	0459 1047 1713 2328	3.5 0.6 3.9 0.3
62 T 9	0414 1010 1641 2303	3.5 0.1 4.5 -0.1	46 W24	0544 1138 1759	3.7 0.5 4.0
58 W10	0513 1112 1739 2355	3.9 -0.2 4.7 -0.4	39 T25	0005 0624 1222 1838	0.2 3.9 0.3 4.0
53 T11	0607 1210 1832	4.4 -0.5 4.9	35 F26 A	0039 0659 1301 1913	0.1 4.1 0.1 4.0
51 F12	0043 0658 1304 1923	-0.7 4.8 -0.8 5.0	33 S27 E	0111 0732 1337 1948	0.0 4.3 0.0 4.0
48 S13 E P	0129 0748 1358 2011	-0.9 5.1 -0.9 5.0	33 S28	0143 0805 1414 2021	0.0 4.4 0.0 3.9
49 S14 FM	0216 0837 1450 2101	-1.0 5.4 -0.9 4.8	34 M29 NM	0217 0839 1452 2056	-0.1 4.5 0.0 3.8
49 M15	0302 0926 1543 2150	-0.9 5.4 -0.8 4.5	34 T30	0251 0913 1531 2131	-0.1 4.6 0.0 3.6
50			36 W31	0326 0949 1612 2208	0.0 4.6 0.0 3.5
			40		

NOVEMBER

Day	Time (h. m.)	Ht. (ft.)	Day	Time (h. m.)	Ht. (ft.)
T 1	0404 1029 1656 2250	0.1 4.5 0.1 3.3	F16 N	0506 1139 1808	0.0 4.7 0.0
45 F 2	0447 1114 1744 2338	0.2 4.4 0.3 3.2	56 S17	0014 0600 1235 1905	3.4 0.3 4.4 0.2
49 S 3 S	0534 1203 1838	0.3 4.3 0.3	60 S18	0117 0659 1335 2004	3.3 0.6 4.1 0.3
59 S 4	0034 0630 1302 1937	3.2 0.4 4.3 0.3	62 M19 LQ	0222 0803 1437 2103	3.2 0.7 3.9 0.4
63 M 5 FQ	0137 0734 1405 2038	3.2 0.4 4.2 0.2	59 T20	0324 0909 1536 2155	3.3 0.8 3.7 0.4
67 T 6	0245 0843 1512 2137	3.4 0.3 4.3 0.0	53 W21	0418 1010 1629 2240	3.5 0.7 3.7 0.4
63 W 7	0351 0951 1615 2234	3.7 0.1 4.4 -0.2	47 T22	0505 1103 1716 2320	3.7 0.6 3.7 0.3
59 T 8	0452 1056 1714 2326	4.2 -0.1 4.5 -0.5	41 F23 A E	0546 1149 1759 2357	4.0 0.4 3.7 0.1
55 F 9 E	0547 1155 1809	4.6 -0.4 4.6	38 S24	0624 1231 1837	4.2 0.2 3.7
52 S10	0016 0639 1251 1901	-0.7 5.0 -0.6 4.6	37 S25	0033 0701 1310 1915	0.1 4.4 0.1 3.7
51 S11 P	0103 0730 1344 1952	-0.9 5.3 -0.8 4.6	35 M26	0107 0736 1350 1952	0.0 4.6 0.0 3.7
48 M12 FM	0151 0818 1437 2042	-0.9 5.5 -0.8 4.4	36 T27 NM	0144 0812 1430 2029	-0.1 4.7 0.0 3.6
49 T13	0239 0907 1528 2132	-0.8 5.5 -0.7 4.2	37 W28	0220 0849 1511 2107	-0.1 4.8 -0.1 3.5
49 W14	0326 0956 1620 2223	-0.6 5.3 -0.5 3.9	38 T29	0259 0927 1553 2147	-0.1 4.8 0.0 3.5
50 T15	0414 1046 1713 2317	-0.4 5.0 -0.3 3.7	41 F30 S	0340 1008 1637 2231	-0.1 4.8 0.0 3.4
53			46		

DECEMBER

Day	Time (h. m.)	Ht. (ft.)	Day	Time (h. m.)	Ht. (ft.)
S 1	0425 1054 1725 2320	0.0 4.7 0.1 3.4	S16	0532 1203 1828	0.3 4.3 0.2
50 S 2	0515 1144 1816	0.1 4.6 0.1	51 M17	0039 0625 1254 1918	3.4 0.5 4.0 0.3
56 M 3	0015 0612 1240 1911	3.4 0.2 4.4 0.1	53 T18	0134 0723 1347 2008	3.3 0.7 3.8 0.4
60 T 4	0117 0716 1340 2009	3.5 0.3 4.3 0.0	55 W19 LQ	0230 0822 1442 2058	3.4 0.8 3.6 0.5
65 W 5 FQ	0223 0824 1445 2108	3.7 0.3 4.2 -0.1	54 T20 E A	0325 0921 1536 2145	3.5 0.8 3.5 0.4
64 T 6	0329 0933 1549 2204	4.0 0.2 4.2 -0.3	51 F21	0416 1017 1627 2230	3.7 0.7 3.5 0.3
62 F 7 E	0431 1039 1651 2259	4.4 0.0 4.2 -0.4	47 S22 WS	0503 1110 1715 2313	3.9 0.6 3.5 0.2
57 S 8	0528 1141 1749 2352	4.7 -0.2 4.2 -0.6	43 S23	0546 1158 1801 2354	4.2 0.4 3.5 0.1
54 S 9 P	0622 1238 1844	5.1 -0.4 4.2	42 M24	0628 1243 1843	4.4 0.2 3.5
52 M10	0042 0714 1332 1936	-0.7 5.3 -0.5 4.2	39 T25	0035 0707 1325 1925	0.0 4.6 0.1 3.5
48 T11 FM	0130 0802 1424 2027	-0.7 5.4 -0.6 4.1	41 W26	0115 0748 1408 2004	-0.1 4.8 0.0 3.6
49 W12	0218 0851 1515 2116	-0.6 5.4 -0.5 4.0	40 T27 NM S	0156 0828 1451 2046	-0.2 4.9 -0.1 3.6
47 T13 N	0305 0938 1603 2204	-0.5 5.2 -0.4 3.8	40 F28	0239 0908 1534 2129	-0.3 5.0 -0.2 3.7
47 F14	0354 1025 1652 2254	-0.3 5.0 -0.2 3.6	44 S29	0324 0952 1618 2215	-0.3 5.0 -0.2 3.7
49 S15	0442 1114 1739 2346	0.0 4.6 0.0 3.5	46 S30	0411 1038 1704 2304	-0.2 4.9 -0.2 3.7
49			49 M31	0502 1127 1754	-0.1 4.7 -0.2

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

and Sun at perigee-syzygy, which act to produce augmented high waters and thus enhance their susceptibility to tidal flooding. Accordingly, its influence should be reflected in the calculated value of the $\Delta\omega$-syzygy coefficient, if this is to become a meaningful index of astronomical tidal flooding potential.

One of the worst instances of tidal flooding in recorded history occurred along the mid-Atlantic coast on 1962 March 6–7. The unusually high proxigean spring tide created at this time, assisted by an increased tidal day, was raised to severe flooding proportions by strong, persistent, onshore winds which lasted through five successive high tides. (See chapter 7 for the flooding details published in newspaper accounts of this catastrophic event, as well as associated weather maps, pictures of the flooding, and hourly height tide data corresponding to the dates involved.) The astronomical contributions to this extremely vulnerable tidal flooding event are revealed among the various data and graphs covering this case. The evaluation of the flooding potential Π is shown in table 30. Table 32a gives the predicted tide heights. Fig. 161a depicts the corresponding rate-of-growth tide curves. Similar data are provided for the rest of the year in tables 32b,c,d and fig. 161b to provide a controlled basis for comparison.

In this example, an extremely close proxigee-syzygy alignment which occurred at a mean epoch of March 6.1975 (e.s.t.), having a separation-interval of only -31^{m}, resulted in a lunar parallax value of $\pi = 61'26.6''$ on March 6.19 (e.s.t.). The position of perigee (labeled P in table 32a) occurred at March 6.1868; syzygy (labeled NM in the same table occurred at March 6.2083 (e.s.t.).

The highest high water (5.3 ft at Breakwater Harbor) was predicted for 0813 (e.s.t.) on March 6. The next succeeding higher high water (of the same height) was predicted for 0902 (e.s.t.) on March 7. The difference between these two times is 49^{m} which, when added to the 24^{h} of elapsed time between the consecutive days, expresses the total interval separating the peaks of immediately succeeding higher high waters. This period is equivalent to the length of the tidal day.

In fig. 152a, it will be noted that this increment of 49^{m} represents the minimum value in a curve trough located between two peaks. As described in the discussion on similar tide curves (p. 303), each minimum in the series of which this is a part is due to the effect of tidal priming in reducing the tidal day. However, among the total array of minima appearing throughout the year, it will be observed that those occurring close to a time of perigee-syzygy are located farthest above a baseline corresponding to the next succeeding apogee-syzygy. This uplifting of a curve trough between two crests is clearly due to the compensating effect of perigee in speeding up the Moon's orbital velocity, increasing the necessary catch-up time of the rotating Earth, and thus lengthening the tidal day. Further, the large π defines a condition of proxigee.

The maximum increase in the tidal day at proxigee-syzygy (NM) on March 6.1975 (e.s.t.), compared with that at exogee-syzygy (FM) on March 20.3944 (e.s.t.) is 16^{m}. The difference involved is larger than that for any other lunation except that containing the date September 14.2374 (e.s.t.), when another perigee-syzygy alignment occurs at full moon. This case has a separation-interval of 11.8^{h} with an accompanying parallax of $\pi = 61'22.233''$ on September 14.2. The difference in the length of the tidal day between perigee and apogee is again 16^{m} (fig. 152b).

The incremental values of 15^{m} on February 5.2541 (e.s.t.), and April 4.1406 (e.s.t.), correspond to two other perigee-syzygy dates in the year, with separation-intervals of 21.8^{h} and -22.8^{h}, respectively. The third 15^{m} increment on October 13.1156 (e.s.t.) is associated with yet another perigee-syzygy alignment in this same unusual year, having a separation-interval of -9.6^{h} and a value of $\pi = 61'25.808''$ on October 12.8 (e.s.t.).

The corresponding values of the $\Delta\omega$-syzygy coefficients for each of the above dates, as derived from table 16, are all above average. Thus, the $\Delta\omega$-syzygy coefficients not only indicate very accurately the times of production of perigean (or proxigean) spring tides but (as a direct function of their magnitudes) denote, in relative degree, the amplified heights of the high waters which result.

Various other astronomical influences resulting from the changing interrelationships of the Moon and Sun may be studied in detail by the combined use of tables 31a,b,c,d and figs. 152a,b. In these tables, the following symbolic designations are used:

S = the date on which the Moon is at its greatest declination south of the Equator
E = the date on which the Moon crosses the Equator
N = the date on which the Moon is at its greatest declination north of the Equator
P = the date of perigee (or proxigee)
A = the date of apogee (or exogee)
NM = new moon
FQ = first quarter moon
FM = full moon
LQ = last quarter moon
VE = the vernal equinox

J–85 (a)

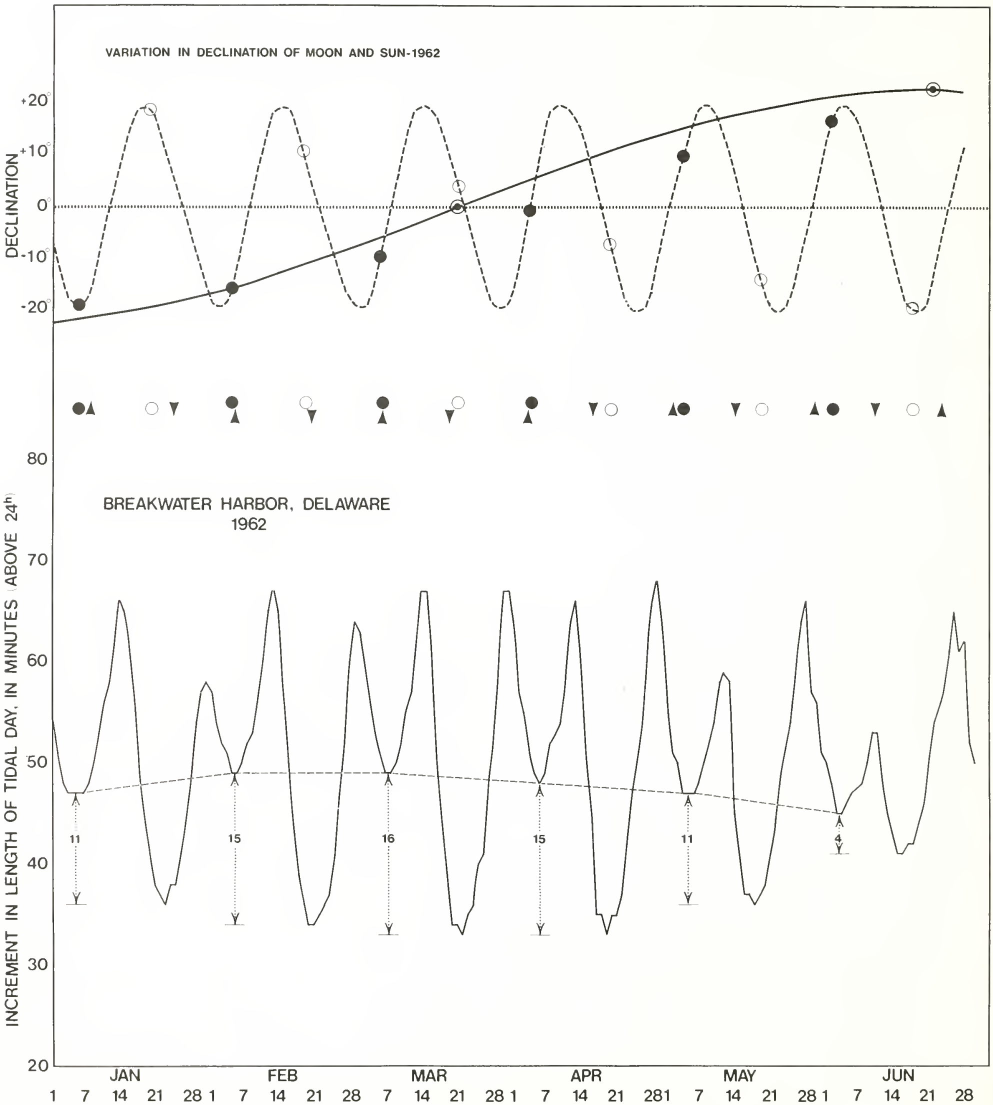

FIGURE 152a.—(Discussed in text.)

J–85 (b)

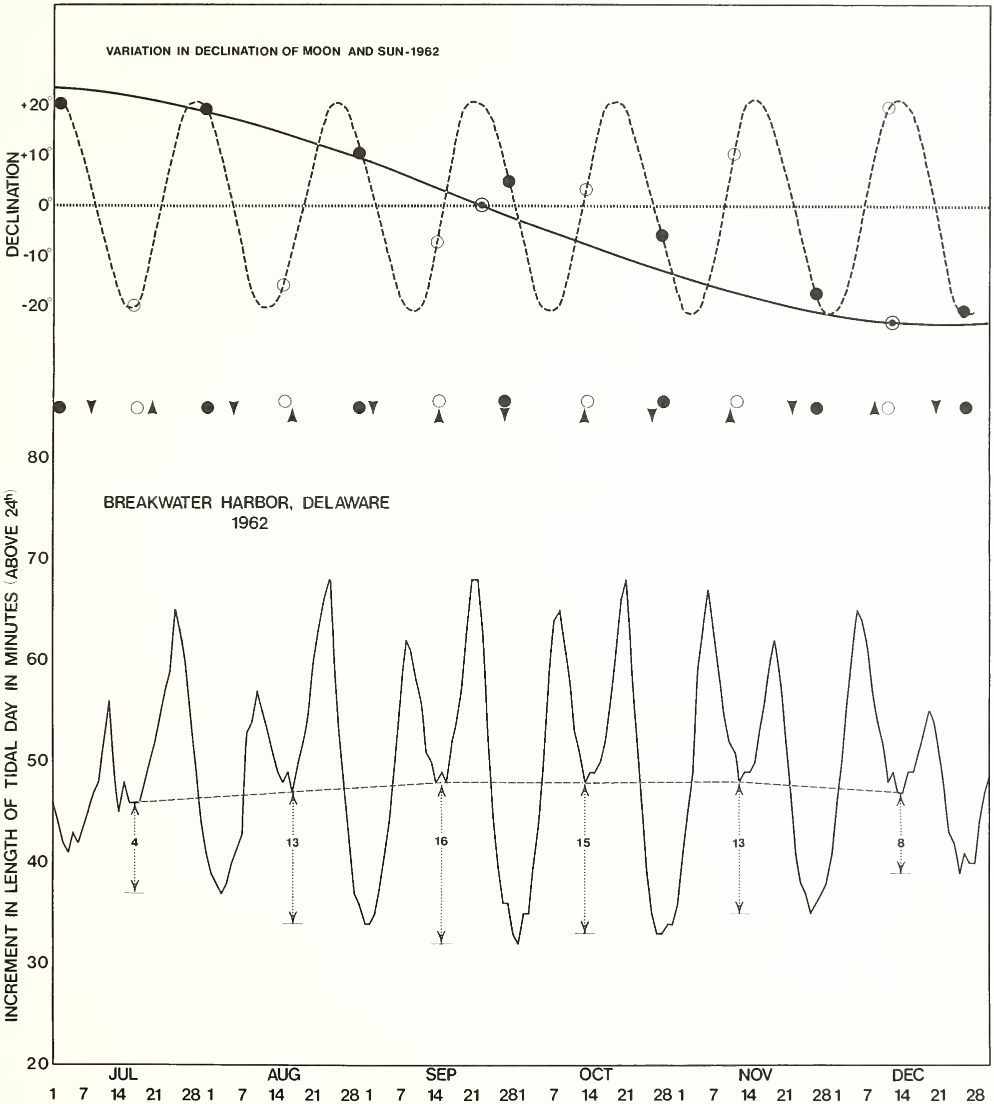

Figure 152b.—(Discussed in text.)

SS= the summer solstice
AE= the autumnal equinox
WS= the winter solstice

The symbols used in figs. 152a,b are indicated in the legend accompanying fig. 153a. At the top of each of these composite diagrams, the continually varying declinations of both the Moon and Sun are plotted to the same scale as that used for the changing lengths of the tidal day in the bottom portion of the diagram. A direct analysis of any contribution to the length of the tidal day made by the changing lunar declination, or by the declinational influence of the Sun, is thus possible.

An obvious disruption of the otherwise uniform, double crests of the curves which occur individually near the Moon's semimonthly positions of quadrature is evident at the time of the summer solstice. The resulting curve irregularities are clearly due to a superposition of the diurnal influence of the Sun, exerted at a time when the solar body is at its maximum positive declination (i.e., at its greatest incursion into the Northern Hemisphere) while the Moon is at a large southern declination.

In fig. 152a, a bifurcated curve peak occurs shortly after the summer solstice on June 21, 21^h24^m. This is followed by a jagged and not readily identifiable minimum about the middle of July as the Moon and Sun again move to nearly maximum opposing declinations.

This effect is not as pronounced when the Sun reaches its maximum negative declination at the winter solstice (December 22, 08^h15^m). Since the Sun is then in the Southern Hemisphere, its influence on the Northern Hemisphere tides is somewhat reduced.

With the Sun and Moon nearly at the same declinations and crossing the Equator on March 21 and 22, respectively, the heights of the two adjacent crests on either side of these dates are very nearly equal. As the dates of the summer and winter solstices are approached, the heights of any two contiguous peaks become the most disparate.

Accelerated Rate of Tide Rise as an Indication of Increased Tidal Flooding Potential

The most significant of the empirical factors giving credibility to the use of the $\Delta\omega$-syzygy coefficient is its close relationship with a significantly increased rate of tide rise at times of perigee-syzygy. Curves of rapidly accelerating tide growth may, in turn, be demonstrated to have a very real positive correlation with actual tidal flooding events.

The point of departure for verifying this relationship is, again, basic data abstracted from the annual tide tables. In contrast with the previously constructed curves involving the length of the tidal day, however, the present curves utilize the average rate of tide rise at a given station during any day of the year as the ordinate value. Depending upon the characteristic type of tide found at the station, one of two different procedures is used in the ensuing analysis.

1. Semidiurnal Tide

To achieve the appropriate curve-plotting values in this case, the difference (in feet or meters) is taken between the predicted level of the lowest low water for any given date and that of the highest high water next following it (even if this HHW occurs early in the morning of the next succeeding date). As will be explained in the next section, if—as frequently happens on the west coast of North America—the lower high water (LHW) sequentially follows the lowest low water, a slightly different procedure is used. Negative low-water values (indicating water levels below the standard chart datum) are, of course, treated algebraically in making the subtraction leading to the total maximum rise in water level. (See tables 32a, b, c, d.)

To obtain the average rate of rise, it only remains to subtract the time of LLW for any date from the time of the next succeeding HHW, and to divide the difference into that giving the corresponding change in water level over this same time interval. The resulting quotient is plotted against the appropriate date on the abscissa axis of the diagram.

Because of the sizable task of extracting and plotting these differences and quotients in each case for 365 days in the year, various representative examples from among the 100 cases of tidal flooding noted in table 1 have been used to show the resulting correlations. Table 33 lists appropriate standard tide-prediction stations either at the scene of the flooding or close thereto. The principal requirement in the selection is that these examples be variously typical of observed tidal flooding conditions. The examples are randomly distributed in time, including one from each decade over the 56-year period from 1918 to 1974, in latitudes ranging from Halifax, Nova Scotia (44°40′ N.), to Los Angeles, Calif. (33°43′ N.), are located on both the Atlantic and Pacific coasts of North America, occur during all winter months of the year from October to April, and at various times of the day and night.

Tables 32a,b,c,d show a sample of the method of taking the requisite time differences (the tidal height differences are similarly established for these same intervals). Figs. 153–163 depict the predicted curves of astro-

TABLE 32a, b, c, d.—*Data Used to Determine the Accelerated Rate of Tide Rise at Times of Perigee-Syzygy, Superimposed on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

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Times and Heights of High and Low Waters

JANUARY						FEBRUARY						MARCH					
DAY	Time *h. m.*	Ht. *ft.*	DAY	Time *h. m.*	Ht. *ft.*	DAY	Time *h. m.*	Ht. *ft.*	DAY	Time *h. m.*	Ht. *ft.*	DAY	Time *h. m.*	Ht. *ft.*	DAY	Time *h. m.*	Ht. *ft.*
M 1	0359 1005 1612 2217	3.8 0.6 3.5 0.2	T16	0504 1124 1727 2320	4.4 0.3 3.6 0.1	T 1	0504 1125 1725 2323	4.5 0.2 3.5 -0.2	F16	0631 1253 1855	4.4 0.3 3.5	T 1	0330 0954 1558 2158	4.2 0.4 3.3 0.1	F16	0515 1138 1747 2334	4.0 0.5 3.4 0.5
99 T 2	0450 1102 1704 2304	4.1 0.4 3.5 0.0	**113** W17	0600 1222 1822	4.6 0.2 3.5	**127** F 2	0558 1220 1820	4.8 0.0 3.7	**107** S17	0041 0715 1333 1936	0.2 4.4 0.2 3.6	**109** F 2	0433 1057 1701 2300	4.4 0.2 3.5 -0.1	**92** S17	0605 1223 1832	4.1 0.4 3.5
112 W 3	0538 1155 1755 2352	4.4 0.2 3.6 -0.2	**115** T18	0010 0649 1312 1911	0.1 4.7 0.1 3.6	**140** S 3	0016 0650 1312 1913	-0.4 5.1 -0.3 4.0	**113** S18	0123 0754 1408 2012	0.1 4.5 0.1 3.7	**122** S 3	0533 1155 1800 2359	4.7 -0.1 3.9 -0.4	**101** S18	0021 0649 1301 1910	0.3 4.2 0.3 3.7
127 T 4	0625 1245 1843	4.8 0.0 3.7	**119** F19	0057 0733 1355 1954	0.0 4.7 0.1 3.6	**151** S 4	0109 0741 1402 2003	-0.6 5.3 -0.5 4.2	**116** M19	0202 0830 1443 2046	0.0 4.5 0.1 3.8	**138** S 4	0629 1248 1854	5.0 -0.4 4.2	**104** M19	0102 0728 1334 1945	0.2 4.2 0.2 3.9
137 F 5	0039 0712 1333 1932	-0.4 5.0 -0.2 3.8	**119** S20	0139 0814 1434 2034	0.0 4.7 0.1 3.6	**162** M 5	0201 0830 1451 2054	-0.8 5.5 -0.7 4.4	**114** T20	0239 0904 1516 2120	0.0 4.4 0.1 3.9	**152** M 5	0054 0722 1338 1947	-0.7 5.2 -0.6 4.5	**113** T20	0140 0802 1407 2017	0.0 4.3 0.1 4.0
148 S 6	0127 0759 1421 2020	-0.5 5.3 -0.4 4.0	**120** S21	0220 0852 1511 2111	0.0 4.7 0.1 3.6	**164** T 6	0254 0919 1539 2144	-0.9 5.4 -0.8 4.5	**113** W21	0317 0938 1548 2154	0.0 4.3 0.1 3.9	**161** T 6	0148 0813 1427 2036	-0.9 5.3 -0.8 4.8	**116** W21	0217 0836 1439 2050	-0.1 4.3 0.0 4.2
153 S 7	0215 0846 1510 2109	-0.6 5.4 -0.5 4.0	**118** M22	0300 0929 1547 2148	0.0 4.6 0.1 3.6	**159** W 7	0346 1009 1627 2236	-0.8 5.3 -0.7 4.6	**111** T22	0355 1013 1622 2229	0.0 4.2 0.1 4.0	**165** W 7	0241 0902 1514 2126	-1.0 5.3 -0.9 5.0	**115** T22	0254 0909 1511 2123	-0.1 4.2 0.0 4.2
157 M 8	0305 0934 1600 2200	-0.7 5.4 -0.6 4.1	**114** T23	0339 1005 1623 2225	0.1 4.5 0.1 3.6	**149** T 8	0439 1101 1716 2330	-0.7 5.0 -0.6 4.6	**107** F23	0434 1049 1657 2307	0.1 4.1 0.2 4.0	**161** T 8	0333 0951 1602 2215	-1.0 5.1 -0.8 5.0	**115** F23	0331 0943 1545 2158	-0.1 4.1 0.0 4.3
153 T 9	0358 1024 1649 2253	-0.6 5.3 -0.5 4.1	**109** W24	0419 1043 1700 2304	0.1 4.3 0.2 3.6	**132** F 9	0535 1154 1806	-0.4 4.6 -0.4	**100** S24	0515 1126 1735 2348	0.2 3.9 0.2 3.9	**149** F 9	0425 1041 1649 2307	-0.8 4.8 -0.6 4.9	**112** S24	0409 1018 1620 2234	-0.1 3.9 0.1 4.3
142 W10	0451 1117 1741 2349	-0.5 5.0 -0.4 4.1	**100** T25	0501 1121 1738 2344	0.3 4.1 0.3 3.6	**126** S10	0026 0634 1250 1900	4.4 -0.2 4.2 -0.2	**90** S25	0600 1207 1817	0.3 3.6 0.3	**131** S10	0519 1133 1738	-0.5 4.4 -0.4	**112** S25	0450 1056 1658 2314	0.0 3.7 0.1 4.3
127 T11	0548 1213 1834	-0.2 4.7 -0.3	**93** F26	0545 1202 1818	0.4 3.9 0.3	**117** S11	0126 0738 1351 1958	4.3 0.1 3.8 0.1	**95** M26	0034 0650 1254 1904	3.9 0.4 3.4 0.3	**133** S11	0001 0615 1228 1829	4.7 -0.2 4.0 -0.1	**94** M26	0534 1137 1740	0.1 3.5 0.2
116 F12	0050 0651 1311 1931	4.1 0.0 4.4 -0.2	**86** S27	0030 0633 1246 1901	3.6 0.5 3.7 0.4	**104** M12	0231 0847 1458 2059	4.2 0.3 3.5 0.2	**94** T27	0126 0747 1349 1958	3.9 0.5 3.3 0.4	**116** M12	0058 0716 1328 1927	4.4 0.1 3.6 0.2	**105** T27	0000 0623 1225 1828	4.2 0.3 3.3 0.3
113 S13	0152 0758 1414 2029	4.1 0.2 4.0 -0.1	**88** S28	0118 0726 1334 1949	3.7 0.6 3.5 0.4	**100** T13	0338 0959 1607 2201	4.2 0.4 3.4 0.3	**93** W28	0226 0850 1451 2056	4.0 0.5 3.2 0.3	**102** T13	0200 0822 1435 2029	4.2 0.4 3.3 0.5	**102** W28	0052 0720 1321 1925	4.2 0.4 3.2 0.4
111 S14	0258 0908 1520 2128	4.2 0.3 3.8 0.0	**89** M29	0212 0824 1429 2040	3.8 0.7 3.4 0.4	**97** W14	0443 1107 1712 2301	4.2 0.4 3.3 0.3	**99**			**90** W14	0307 0933 1546 2134	4.1 0.5 3.2 0.6	**96** T29	0152 0822 1426 2028	4.1 0.4 3.2 0.3
109 M15	0403 1018 1626 2225	4.3 0.3 3.6 0.1	**90** T30	0309 0925 1527 2134	3.9 0.6 3.3 0.3	**100** T15	0541 1205 1807 2355	4.3 0.4 3.4 0.3				**85** T15	0414 1041 1652 2238	4.0 0.5 3.2 0.6	**100** F30	0259 0928 1535 2135	4.2 0.3 3.4 0.2
113			**99** W31	0407 1026 1627 2228	4.2 0.5 3.4 0.1	**104**						**86**			**107** S31	0406 1030 1641 2241	4.4 0.1 3.7 0.0
			111												**118**		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 32a, b, c, d.—*Data Used to Determine the Accelerated Rate of Tide Rise at Times of Perigee-Syzygy, Superimposed on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

BREAKWATER HARBOR, DEL., 1962 75

Times and Heights of High and Low Waters

APRIL

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
S 1	0510	4.6	M16	0613	3.9
	1129	-0.2		1218	0.3
	1741	4.1		1836	3.9
	2343	-0.4			
135			**103**		
M 2	0607	4.8	T17	0036	0.2
	1222	-0.5		0652	4.0
	1836	4.5		1253	0.2
				1911	4.1
150			**111**		
T 3	0041	-0.7	W18	0114	0.1
	0702	5.0		0729	4.0
	1312	-0.7		1327	0.1
	1928	4.9		1946	4.3
162			**116**		
W 4	0135	-0.9	T19	0152	-0.1
	0753	5.0		0803	4.0
	1400	-0.9		1401	0.0
	2017	5.2		2019	4.4
164			**119**		
T 5	0227	-1.0	F20	0229	-0.2
	0842	5.0		0838	4.0
	1447	-0.9		1435	0.0
	2106	5.3		2054	4.5
158			**121**		
F 6	0319	-0.9	S21	0307	-0.2
	0931	4.7		0914	3.9
	1534	-0.8		1510	0.0
	2154	5.2		2129	4.6
147			**121**		
S 7	0410	-0.8	S22	0347	-0.2
	1021	4.5		0950	3.7
	1621	-0.5		1547	0.0
	2243	5.1		2206	4.6
129			**115**		
S 8	0502	-0.5	M23	0429	-0.1
	1112	4.1		1030	3.6
	1708	-0.2		1627	0.1
	2335	4.8		2248	4.5
105			**112**		
M 9	0555	-0.2	T24	0515	0.0
	1206	3.7		1114	3.5
	1800	0.1		1712	0.2
				2335	4.5
113			**—**		
T10	0029	4.5	W25	0604	0.1
	0653	0.1		1204	3.3
	1306	3.4		1803	0.3
	1855	0.4			
97			**106**		
W11	0127	4.2	T26	0029	4.4
	0755	0.4		0701	0.2
	1411	3.2		1303	3.3
	1956	0.6		1902	0.3
86			**103**		
T12	0231	4.0	F27	0129	4.3
	0901	0.5		0801	0.2
	1520	3.2		1409	3.4
	2102	0.8		2008	0.3
76			**103**		
F13	0337	3.8	S28	0235	4.3
	1002	0.5		0904	0.1
	1622	3.3		1518	3.6
	2206	0.7		2118	0.2
79			**106**		
S14	0437	3.8	S29	0343	4.3
	1056	0.5		1004	-0.1
	1714	3.4		1623	3.9
	2304	0.6		2225	0.0
86			**120**		
S15	0528	3.9	M30	0446	4.4
	1140	0.4		1102	-0.3
	1759	3.7		1723	4.4
	2354	0.4		2328	-0.3
95			**138**		

MAY

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
T 1	0545	4.5	W16	0001	0.3
	1155	-0.5		0610	3.7
	1818	4.8		1207	0.2
				1835	4.2
151			**114**		
W 2	0027	-0.5	T17	0043	0.1
	0640	4.6		0650	3.8
	1245	-0.7		1245	0.1
	1909	5.1		1912	4.5
158			**119**		
T 3	0121	-0.7	F18	0124	0.0
	0732	4.6		0729	3.8
	1333	-0.8		1322	0.0
	1959	5.3		1948	4.6
158			**127**		
F 4	0213	-0.8	S19	0203	-0.1
	0822	4.5		0807	3.7
	1420	-0.7		1400	-0.1
	2046	5.4		2025	4.8
153			**130**		
S 5	0304	-0.8	S20	0245	-0.2
	0911	4.3		0846	3.7
	1507	-0.6		1438	-0.1
	2133	5.3		2103	4.9
142			**130**		
S 6	0354	-0.6	M21	0327	-0.2
	1001	4.1		0926	3.6
	1553	-0.4		1520	-0.1
	2220	5.1		2144	4.9
127			**125**		
M 7	0444	-0.4	T22	0412	-0.2
	1051	3.8		1009	3.5
	1641	-0.1		1603	0.0
	2308	4.8		2228	4.8
100			**122**		
T 8	0535	-0.2	W23	0459	-0.1
	1144	3.5		1058	3.5
	1730	0.2		1652	0.0
				2317	4.7
110			**—**		
W 9	0000	4.5	T24	0549	-0.1
	0627	0.1		1151	3.5
	1240	3.3		1746	0.2
	1824	0.5			
95			**114**		
T10	0054	4.2	F25	0011	4.6
	0723	0.3		0643	0.0
	1340	3.2		1250	3.5
	1923	0.7		1847	0.2
82			**110**		
F11	0152	3.9	S26	0110	4.4
	0819	0.4		0741	0.0
	1442	3.2		1355	3.6
	2026	0.8		1954	0.3
75			**105**		
S12	0251	3.7	S27	0214	4.3
	0914	0.5		0840	-0.1
	1540	3.3		1502	3.9
	2129	0.8		2103	0.2
76			**114**		
S13	0349	3.7	M28	0320	4.2
	1003	0.5		0939	-0.2
	1632	3.5		1605	4.2
	2225	0.7		2210	0.1
88			**123**		
M14	0441	3.7	T29	0424	4.2
	1049	0.4		1035	-0.3
	1717	3.8		1704	4.5
	2316	0.5		2314	-0.1
95			**135**		
T15	0528	3.7	W30	0524	4.2
	1130	0.3		1128	-0.4
	1758	4.0		1800	4.9
103			**143**		
			T31	0013	-0.3
				0620	4.2
				1219	-0.5
				1851	5.1
			147		

JUNE

Day	Time h. m.	Ht. ft.	Day	Time h. m.	Ht. ft.
F 1	0108	-0.5	S16	0056	0.1
	0713	4.1		0655	3.6
	1307	-0.5		1246	-0.1
	1941	5.3		1919	4.8
148			**132**		
S 2	0200	-0.5	S17	0139	-0.1
	0803	4.1		0738	3.6
	1355	-0.5		1328	-0.2
	2028	5.3		2001	5.0
143			**138**		
S 3	0250	-0.5	M18	0223	-0.2
	0853	3.9		0821	3.6
	1442	-0.4		1412	-0.3
	2113	5.2		2043	5.1
133			**139**		
M 4	0338	-0.4	T19	0308	-0.3
	0941	3.8		0906	3.7
	1528	-0.2		1459	-0.3
	2158	5.0		2127	5.1
118			**135**		
T 5	0424	-0.3	W20	0355	-0.3
	1029	3.6		0953	3.7
	1615	0.1		1547	-0.2
	2244	4.7		2213	5.0
106			**133**		
W 6	0511	-0.1	T21	0442	-0.3
	1119	3.5		1044	3.7
	1703	0.3		1639	-0.2
	2331	4.4		2303	4.9
89			**123**		
T 7	0558	0.1	F22	0532	-0.3
	1209	3.4		1138	3.7
	1753	0.5		1734	0.0
				2357	4.7
93			**110**		
F 8	0019	4.1	S23	0624	-0.3
	0645	0.3		1236	3.8
	1303	3.3		1835	0.1
	1847	0.7			
84			**116**		
S 9	0109	3.9	S24	0054	4.5
	0733	0.4		0719	-0.2
	1356	3.3		1338	3.9
	1945	0.8		1940	0.2
77			**107**		
S10	0202	3.7	M25	0155	4.2
	0822	0.4		0816	-0.2
	1450	3.4		1443	4.1
	2043	0.8		2048	0.2
82			**117**		
M11	0255	3.6	T26	0300	4.1
	0909	0.4		0913	-0.2
	1541	3.6		1546	4.4
	2140	0.7		2157	0.1
89			**121**		
T12	0349	3.5	W27	0403	3.9
	0956	0.3		1009	-0.2
	1629	3.8		1647	4.6
	2233	0.6		2302	0.0
96			**128**		
W13	0439	3.5	T28	0505	3.8
	1040	0.3		1104	-0.3
	1714	4.1		1743	4.8
	2323	0.4			
104			**133**		
T14	0526	3.5	F29	0003	-0.1
	1123	0.2		0603	3.8
	1757	4.3		1157	-0.3
				1835	5.0
117			**136**		
F15	0010	0.2	S30	0058	-0.2
	0611	3.5		0658	3.8
	1204	0.0		1247	-0.3
	1838	4.6		1925	5.1
125			**134**		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 32a, b, c, d.—*Data Used to Determine the Accelerated Rate of Tide Rise at Times of Perigee-Syzygy, Superimposed on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

76 **BREAKWATER HARBOR, DEL., 1962**

Times and Heights of High and Low Waters

JULY

Day	Time (h. m.)	Ht. (ft.)	
S 1	0148 0749 1334 2011	-0.3 3.7 -0.2 5.1	**132**
M 2	0235 0836 1421 2055	-0.3 3.7 -0.2 5.0	**123**
T 3	0319 0921 1506 2137	-0.2 3.6 0.0 4.8	**116**
W 4	0402 1004 1551 2218	-0.1 3.6 0.1 4.6	**109**
T 5	0442 1049 1636 2301	0.0 3.5 0.2 4.4	**97**
F 6	0523 1134 1722 2343	0.1 3.5 0.4 4.1.	**88**
S 7	0603 1219 1810	0.2 3.5 0.5	**90**
S 8	0028 0646 1307 1902	3.9 0.3 3.5 0.7	**80**
M 9	0115 0731 1356 1957	3.7 0.3 3.6 0.7	**84**
T10	0203 0817 1448 2054	3.5 0.4 3.7 0.7	**91**
W11	0257 0904 1540 2150	3.4 0.3 3.9 0.7	**95**
T12	0351 0952 1630 2245	3.3 0.3 4.1 0.5	**103**
F13	0443 1040 1719 2337	3.3 0.2 4.3 0.3	**116**
S14	0534 1128 1804	3.4 0.0 4.6	**126**
S15	0027 0623 1216 1852	0.1 3.5 -0.1 4.9	**137**

Day	Time (h. m.)	Ht. (ft.)	
M16	0115 0711 1303 1938	-0.1 3.6 -0.3 5.1	**143**
T17	0201 0759 1352 2024	-0.3 3.7 -0.4 5.2	**149**
W18	0247 0847 1442 2110	-0.4 3.9 -0.5 5.3	**148**
T19	0334 0936 1533 2158	-0.5 4.0 -0.5 5.2	**141**
F20	0421 1027 1626 2248	-0.6 4.1 -0.4 5.0	**132**
S21	0510 1121 1722 2340	-0.5 4.2 -0.3 4.7	**122**
S22	0601 1218 1821	-0.4 4.2 -0.1	**120**
M23	0037 0654 1318 1925	4.4 -0.3 4.3 0.1	**115**
T24	0136 0750 1421 2033	4.1 -0.2 4.3 0.2	**113**
W25	0240 0848 1526 2143	3.8 -0.1 4.4 0.2	**112**
T26	0346 0946 1629 2251	3.6 0.0 4.5 0.2	**117**
F27	0452 1045 1728 2353	3.5 0.0 4.7 0.1	**119**
S28	0552 1140 1822	3.5 0.0 4.8	**120**
S29	0047 0646 1232 1911	0.0 3.5 0.0 4.8	**121**
M30	0134 0735 1319 1955	0.0 3.6 0.0 4.8	**120**
T31	0216 0819 1403 2036	-0.1 3.6 0.0 4.7	**119**

AUGUST

Day	Time (h. m.)	Ht. (ft.)	
W 1	0255 0859 1446 2114	-0.1 3.7 0.0 4.6	**115**
T 2	0332 0937 1528 2152	0.0 3.7 0.1 4.5	**108**
F 3	0408 1015 1609 2229	0.0 3.7 0.2 4.3	**104**
S 4	0444 1054 1651 2307	0.1 3.7 0.2 4.1	**94**
S 5	0521 1135 1736 2347	0.2 3.7 0.4 3.9	**93**
M 6	0600 1218 1823	0.2 3.7 0.5	**89**
T 7	0030 0642 1305 1914	3.6 0.3 3.7 0.6	**87**
W 8	0117 0727 1357 2010	3.4 0.4 3.8 0.7	**89**
T 9	0208 0816 1451 2109	3.3 0.4 3.9 0.7	**95**
F10	0305 0908 1548 2207	3.2 0.3 4.1 0.6	**102**
S11	0404 1002 1643 2305	3.2 0.2 4.3 0.3	**113**
S12	0502 1058 1736 2359	3.3 0.1 4.6 0.1	**129**
M13	0557 1151 1827	3.5 -0.2 4.9	**140**
T14	0049 0649 1243 1916	-0.2 3.8 -0.4 5.1	**152**
W15	0136 0739 1335 2004	-0.4 4.0 -0.6 5.3	**155**

Day	Time (h. m.)	Ht. (ft.)	
T16	0223 0828 1427 2053	-0.6 4.3 -0.7 5.3	**157**
F17	0310 0917 1519 2140	-0.8 4.5 -0.8 5.2	**151**
S18	0357 1007 1613 2230	-0.8 4.6 -0.7 5.0	**141**
S19	0445 1100 1708 2322	-0.7 4.6 -0.5 4.6	**136**
M20	0534 1155 1805	-0.6 4.6 -0.2	**123**
T21	0017 0626 1255 1908	4.3 -0.3 4.5 0.0	**114**
W22	0117 0722 1358 2017	3.9 -0.1 4.4 0.2	**107**
T23	0222 0822 1504 2129	3.6 0.1 4.4 0.3	**103**
F24	0333 0926 1612 2239	3.4 0.2 4.4 0.3	**101**
S25	0441 1029 1713 2340	3.3 0.3 4.4 0.2	**108**
S26	0542 1128 1806	3.4 0.2 4.5	**109**
M27	0032 0634 1219 1854	0.1 3.5 0.2 4.5	**112**
T28	0114 0718 1304 1936	0.1 3.6 0.1 4.5	**116**
W29	0151 0757 1345 2013	0.0 3.8 0.0 4.5	**115**
T30	0225 0832 1425 2049	0.0 3.9 0.0 4.4	**113**
F31	0259 0906 1503 2123	0.0 3.9 0.0 4.3	**112**

SEPTEMBER

Day	Time (h. m.)	Ht. (ft.)	
S 1	0331 0941 1542 2157	0.0 4.0 0.0 4.2	**107**
S 2	0403 1016 1622 2232	0.0 4.0 0.1 4.0	**104**
M 3	0439 1054 1703 2309	0.1 4.0 0.2 3.7	**100**
T 4	0516 1135 1748 2350	0.2 4.0 0.4 3.5	**94**
W 5	0556 1220 1837	0.3 3.9 0.5	**90**
T 6	0036 0642 1310 1933	3.3 0.4 3.9 0.6	**92**
F 7	0129 0733 1406 2033	3.1 0.4 4.0 0.6	**93**
S 8	0229 0831 1508 2136	3.1 0.4 4.1 0.5	**101**
S 9	0334 0931 1609 2235	3.1 0.3 4.3 0.3	**114**
M10	0437 1032 1707 2331	3.3 0.1 4.6 0.0	**127**
T11	0534 1130 1803	3.7 -0.2 4.8	**144**
W12	0023 0628 1226 1854	-0.3 4.0 -0.5 5.1	**153**
T13	0110 0718 1319 1944	-0.6 4.4 -0.7 5.2	**161**
F14	0157 0807 1412 2032	-0.8 4.7 -0.9 5.2	**159**
S15	0243 0857 1504 2121	-0.9 5.0 -0.9 5.1	**160**

Day	Time (h. m.)	Ht. (ft.)	
S16	0330 0946 1558 2209	-0.9 5.1 -0.8 4.8	**152**
M17	0417 1038 1652 2302	-0.8 5.0 -0.6 4.4	**140**
T18	0506 1132 1749 2357	-0.5 4.9 -0.3 4.0	**125**
W19	0558 1230 1850	-0.2 4.7 0.0	**108**
T20	0058 0655 1333 1959	3.7 0.1 4.4 0.2	**99**
F21	0205 0758 1441 2111	3.4 0.3 4.3 0.4	**92**
S22	0319 0905 1549 2220	3.2 0.5 4.2 0.4	**93**
S23	0429 1012 1652 2319	3.3 0.5 4.2 0.3	**97**
M24	0527 1112 1745	3.4 0.4 4.2	**101**
T25	0005 0614 1203 1830	0.2 3.6 0.3 4.2	**107**
W26	0045 0655 1246 1910	0.1 3.8 0.2 4.3	**110**
T27	0119 0730 1325 1946	0.1 3.9 0.1 4.3	**111**
F28	0150 0802 1402 2020	0.0 4.1 0.0 4.2	**112**
S29	0221 0836 1439 2053	0.0 4.2 0.0 4.1	**115**
S30	0253 0908 1516 2125	0.0 4.3 0.0 4.0	**114**

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 32a, b, c, d.—*Data Used to Determine the Accelerated Rate of Tide Rise at Times of Perigee-Syzygy, Superimposed on the National Ocean Survey Tide Tables for Breakwater Harbor, Del., January–December, 1962*

BREAKWATER HARBOR, DEL., 1962 77

Times and Heights of High and Low Waters

OCTOBER

Day	Time h. m.	Ht. ft.
M 1	0326 0943 1555 2159	0.0 4.3 0.0 3.8
111		
T 2	0400 1018 1635 2236	0.1 4.3 0.1 3.6
105		
W 3	0437 1058 1719 2316	0.2 4.2 0.3 3.4
104		
T 4	0517 1142 1807	0.2 4.2 0.4
95		
F 5	0002 0602 1232 1902	3.2 0.4 4.1 0.5
94		
S 6	0057 0657 1330 2003	3.1 0.4 4.1 0.5
94		
S 7	0200 0759 1434 2106	3.1 0.4 4.1 0.4
101		
M 8	0308 0904 1539 2206	3.2 0.3 4.3 0.2
113		
T 9	0414 1010 1641 2303	3.5 0.1 4.5 -0.1
127		
W10	0513 1112 1739 2355	3.9 -0.2 4.7 -0.4
141		
T11	0607 1210 1832	4.4 -0.5 4.9
153		
F12	0043 0658 1304 1923	-0.7 4.8 -0.8 5.0
158		
S13	0129 0748 1358 2011	-0.9 5.1 -0.9 5.0
168		
S14	0216 0837 1450 2101	-1.0 5.4 -0.9 4.8
164		
M15	0302 0926 1543 2150	-0.9 5.4 -0.8 4.5
158		

Day	Time h. m.	Ht. ft.
T16	0351 1016 1636 2242	-0.8 5.3 -0.6 4.2
141		
W17	0439 1108 1732 2337	-0.5 5.0 -0.3 3.8
122		
T18	0531 1204 1831	-0.1 4.7 0.0
106		
F19	0038 0627 1305 1936	3.5 0.2 4.4 0.2
90		
S20	0146 0730 1411 2044	3.3 0.5 4.1 0.4
82		
S21	0258 0838 1519 2148	3.2 0.7 4.0 0.4
81		
M22	0403 0946 1620 2244	3.3 0.7 3.9 0.4
85		
T23	0459 1047 1713 2328	3.5 0.6 3.9 0.3
92		
W24	0544 1138 1759	3.7 0.5 4.0
98		
T25	0005 0624 1222 1838	0.2 3.9 0.3 4.0
105		
F26	0039 0659 1301 1913	0.1 4.1 0.1 4.0
113		
S27	0111 0732 1337 1948	0.0 4.3 0.0 4.0
115		
S28	0143 0805 1414 2021	0.0 4.4 0.0 3.9
120		
M29	0217 0839 1452 2056	-0.1 4.5 0.0 3.8
123		
T30	0251 0913 1531 2131	-0.1 4.6 0.0 3.6
120		
W31	0326 0949 1612 2208	0.0 4.6 0.0 3.5
114		

NOVEMBER

Day	Time h. m.	Ht. ft.
T 1	0404 1029 1656 2250	0.1 4.5 0.1 3.3
109		
F 2	0447 1114 1744 2338	0.2 4.4 0.3 3.2
103		
S 3	0534 1203 1838	0.3 4.3 0.3
99		
S 4	0034 0630 1302 1937	3.2 0.4 4.3 0.3
97		
M 5	0137 0734 1405 2038	3.2 0.4 4.2 0.2
103		
T 6	0245 0843 1512 2137	3.4 0.3 4.3 0.0
112		
W 7	0351 0951 1615 2234	3.7 0.1 4.4 -0.2
112		
T 8	0452 1056 1714 2326	4.2 -0.1 4.5 -0.5
122		
F 9	0547 1155 1809	4.6 -0.4 4.6
130		
S10	0016 0639 1251 1901	-0.7 5.0 -0.6 4.6
149		
S11	0103 0730 1344 1952	-0.9 5.3 -0.8 4.6
160		
M12	0151 0818 1437 2042	-0.9 5.5 -0.8 4.4
165		
T13	0239 0907 1528 2132	-0.8 5.5 -0.7 4.2
162		
W14	0326 0956 1620 2223	-0.6 5.3 -0.5 3.9
151		
T15	0414 1046 1713 2317	-0.4 5.0 -0.3 3.7
138		

Day	Time h. m.	Ht. ft.
F16	0506 1139 1808	0.0 4.7 0.0
120		
S17	0014 0600 1235 1905	3.4 0.3 4.4 0.2
104		
S18	0117 0659 1335 2004	3.3 0.6 4.1 0.3
88		
M19	0222 0803 1437 2103	3.2 0.7 3.9 0.4
81		
T20	0324 0909 1536 2155	3.3 0.8 3.7 0.4
75		
W21	0418 1010 1629 2240	3.5 0.7 3.7 0.4
79		
T22	0505 1103 1716 2320	3.7 0.6 3.7 0.3
86		
F23	0546 1149 1759 2357	4.0 0.4 3.7 0.1
96		
S24	0624 1231 1837	4.2 0.2 3.7
106		
S25	0033 0701 1310 1915	0.1 4.4 0.1 3.7
111		
M26	0107 0736 1350 1952	0.0 4.6 0.0 3.7
118		
T27	0144 0812 1430 2029	-0.1 4.7 0.0 3.6
124		
W28	0220 0849 1511 2107	-0.1 4.8 -0.1 3.5
126		
T29	0259 0927 1553 2147	-0.1 4.8 0.0 3.5
126		
F30	0340 1008 1637 2231	-0.1 4.8 0.0 3.4
126		

DECEMBER

Day	Time h. m.	Ht. ft.
S 1	0425 1054 1725 2320	0.0 4.7 0.1 3.4
121		
S 2	0515 1144 1816	0.1 4.6 0.1
116		
M 3	0015 0612 1240 1911	3.4 0.2 4.4 0.1
108		
T 4	0117 0716 1340 2009	3.5 0.3 4.3 0.0
104		
W 5	0223 0824 1445 2108	3.7 0.3 4.2 -0.1
102		
T 6	0329 0933 1549 2204	4.0 0.2 4.2 -0.3
106		
F 7	0431 1039 1651 2259	4.4 0.0 4.2 -0.4
113		
S 8	0528 1141 1749 2352	4.7 -0.2 4.2 -0.6
131		
S 9	0622 1238 1844	5.1 -0.4 4.2
146		
M10	0042 0714 1332 1936	-0.7 5.3 -0.5 4.2
153		
T11	0130 0802 1424 2027	-0.7 5.4 -0.6 4.1
156		
W12	0218 0851 1515 2116	-0.6 5.4 -0.5 4.0
153		
T13	0305 0938 1603 2204	-0.5 5.2 -0.4 3.8
145		
F14	0354 1025 1652 2254	-0.3 5.0 -0.2 3.6
136		
S15	0442 1114 1739 2346	0.0 4.6 0.0 3.5
117		

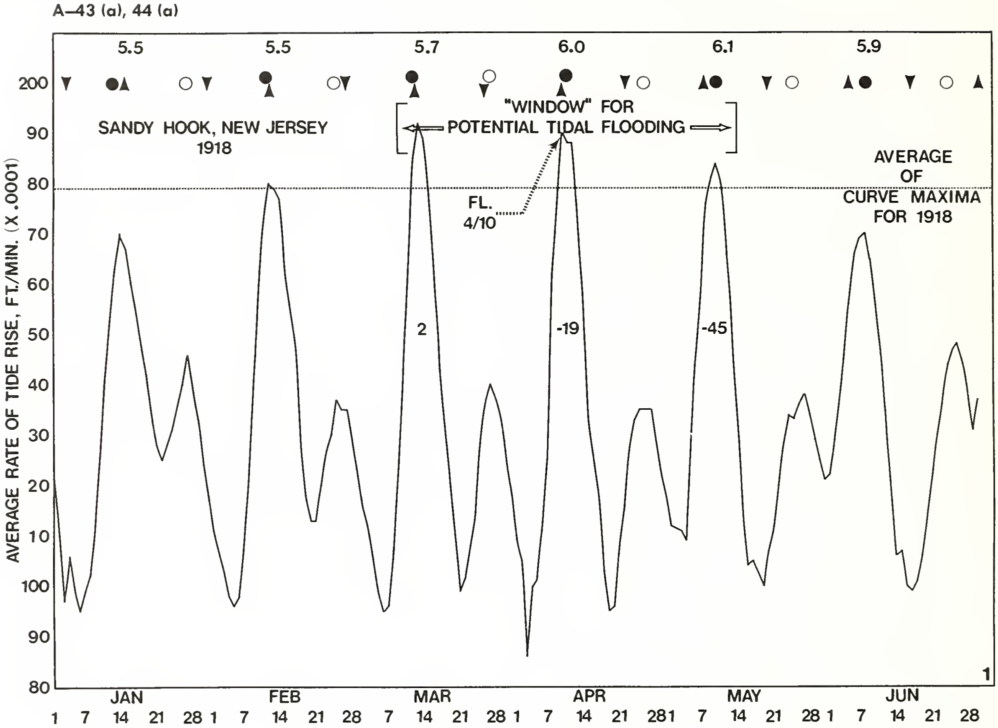
Day	Time h. m.	Ht. ft.
S16	0532 1203 1828	0.3 4.3 0.2
102		
M17	0039 0625 1254 1918	3.4 0.5 4.0 0.3
90		
T18	0134 0723 1347 2008	3.3 0.7 3.8 0.4
81		
W19	0230 0822 1442 2058	3.4 0.8 3.6 0.5
74		
T20	0325 0921 1536 2145	3.5 0.8 3.5 0.4
78		
F21	0416 1017 1627 2230	3.7 0.7 3.5 0.3
84		
S22	0503 1110 1715 2313	3.9 0.6 3.5 0.2
92		
S23	0546 1158 1801 2354	4.2 0.4 3.5 0.1
102		
M24	0628 1243 1843	4.4 0.2 3.5
109		
T25	0035 0707 1325 1925	0.0 4.6 0.1 3.5
117		
W26	0115 0748 1408 2004	-0.1 4.8 0.0 3.6
125		
T27	0156 0828 1451 2046	-0.2 4.9 -0.1 3.6
130		
F28	0239 0908 1534 2129	-0.3 5.0 -0.2 3.7
136		
S29	0324 0952 1618 2215	-0.3 5.0 -0.2 3.7
137		
S30	0411 1038 1704 2304	-0.2 4.9 -0.2 3.7
132		
M31	0502 1127 1754	-0.1 4.7 -0.2
125		

Time meridian 75° W. 0000 is midnight. 1200 is noon.

Heights are reckoned from the datum of soundings on charts of the locality which is mean low water.

TABLE 33.—*Sixteen Instances of Major Tidal Flooding Near a Time of Perigee-Syzygy, Represented (in Figs. 153–163) by Plots Showing the Predicted Rate of Rise of the Astronomical Tide at Nearby Tidal Reference Stations (Listed in the Table)*

Tidal reference station used	Dates of flooding	Key letter and serial No.
SANDY HOOK, N.J., 1918		
Part (a): Jan. 1–June 30	4/10–12	A–43(a); 44(a)
Part (b): July 1–Dec. 31	11/18	A–43(b); 44(b)
NEWPORT, R.I., 1927		
Part (a): Jan. 1–June 30	3/3–4; 4/2	B–50(a); C–51(a), 52(a)
Part (b): July 1–Dec. 31	12/5	B–50(b); C–51(b), 52(b)
PORTLAND, ME., 1940		
Part (a): Jan. 1–June 30	4/21	G–69(a)
Part (b): July 1–Dec. 31		G–69(b)
EASTPORT, ME., 1945		
Part (a): Jan. 1–June 30		H–72(a)
Part (b): July 1–Dec. 31	11/20	H–72(b)
HALIFAX, NOVA SCOTIA, 1973–74		
Part (b): Oct. 1–Mar. 31	12/11	M–98e
ABERDEEN, WASH., 1973–74		
Part (b): Oct. 1–Mar. 31	12/11	M–98w
WILLETS POINT, N.Y., 1931		
Part (a): Jan. 1–June 30	3/4–8; 4/1	D–57(a); E–58(a)
Part (b): July 1–Dec. 31		D–57(b); E–58(b)
BOSTON, MASS., 1959–60		
Part (a): Jan. 1–June 30		I–83e(a)
Part (b): July 1–Jan. 7	12/29	I–83e(b)
BREAKWATER HARBOR, DEL., 1962		
Part (a): Jan. 1–June 30	3/6–7	J–85(a); K–87(a)
Part (b): July 1–Dec. 31	11/10–14	J–85(b); K–87(b)
ASTORIA, OREG., 1962		
Part (a): Jan. 1–June 30		86(a)
Part (b): July 1–Dec. 31	10/13	86(b)
LOS ANGELES, CALIF., 1974		
Part (a): Dec. 1–May 31	1/8	N–99(a)
Part (b): June 1–Nov. 30		N–99(b)



Note: The bracketed "windows" of potential tidal flooding pertain only to the higher of the two peaks indicating maximum rate of tide rise in each lunation, and their corresponding dates. The position of the line representing the "average of curve maxima" is computed (see exceptions noted in text) from a 13 lunar-month mean of the higher of these two monthly maxima. A perigee-syzygy series may thus overlap successive calendar years.	▲ Lunar perigee ▼ Lunar apogee ○ Full moon ● New moon	11.4 Maximum tide height in each lunation, in feet and tenths above standard datum -13 Difference, in hours, perigee minus syzygy 1 "One-back" computation method involving tidal phases 3 "Three-back" computation method involving tidal phases

FIGURE 153a.

A–43 (b), 44 (b)

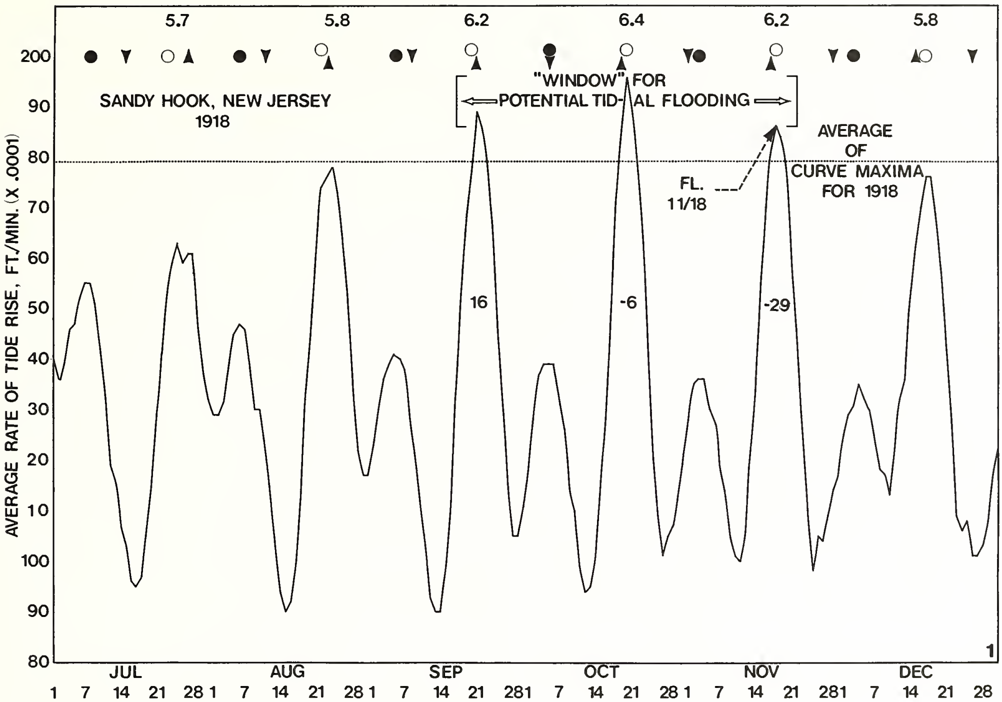


Figure 153b.

B–50 (a), C–51 (a), 52 (a)

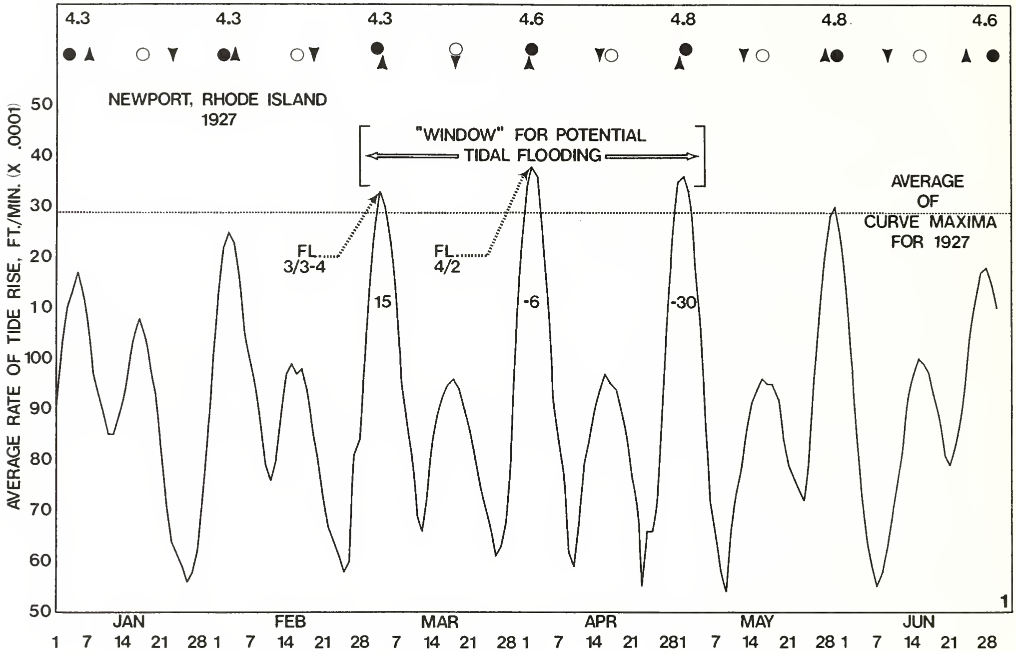


FIGURE 154a.

B–50 (b), C–51 (b), 52 (b)

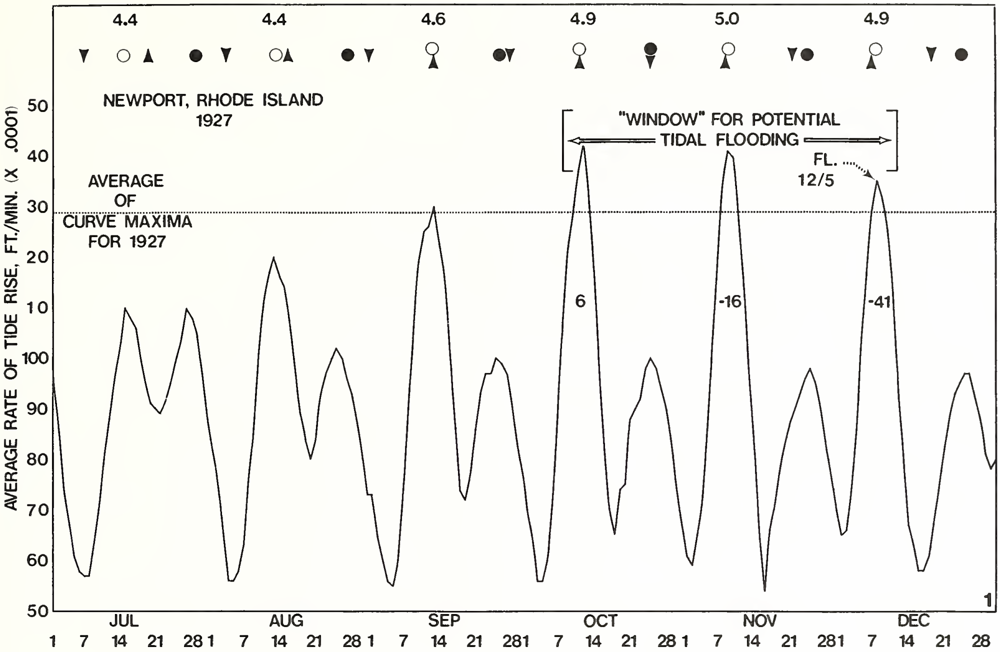


FIGURE 154b.

G-69 (a)

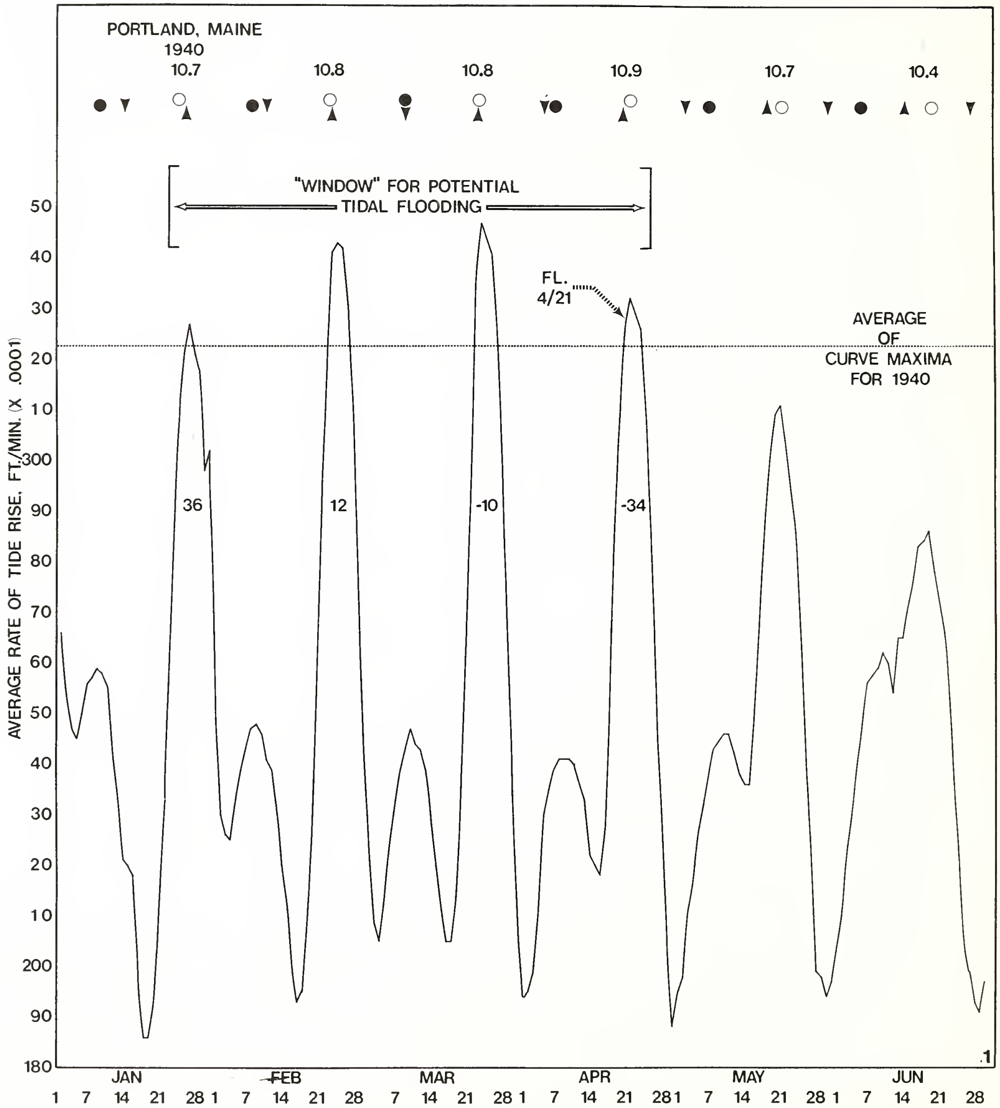
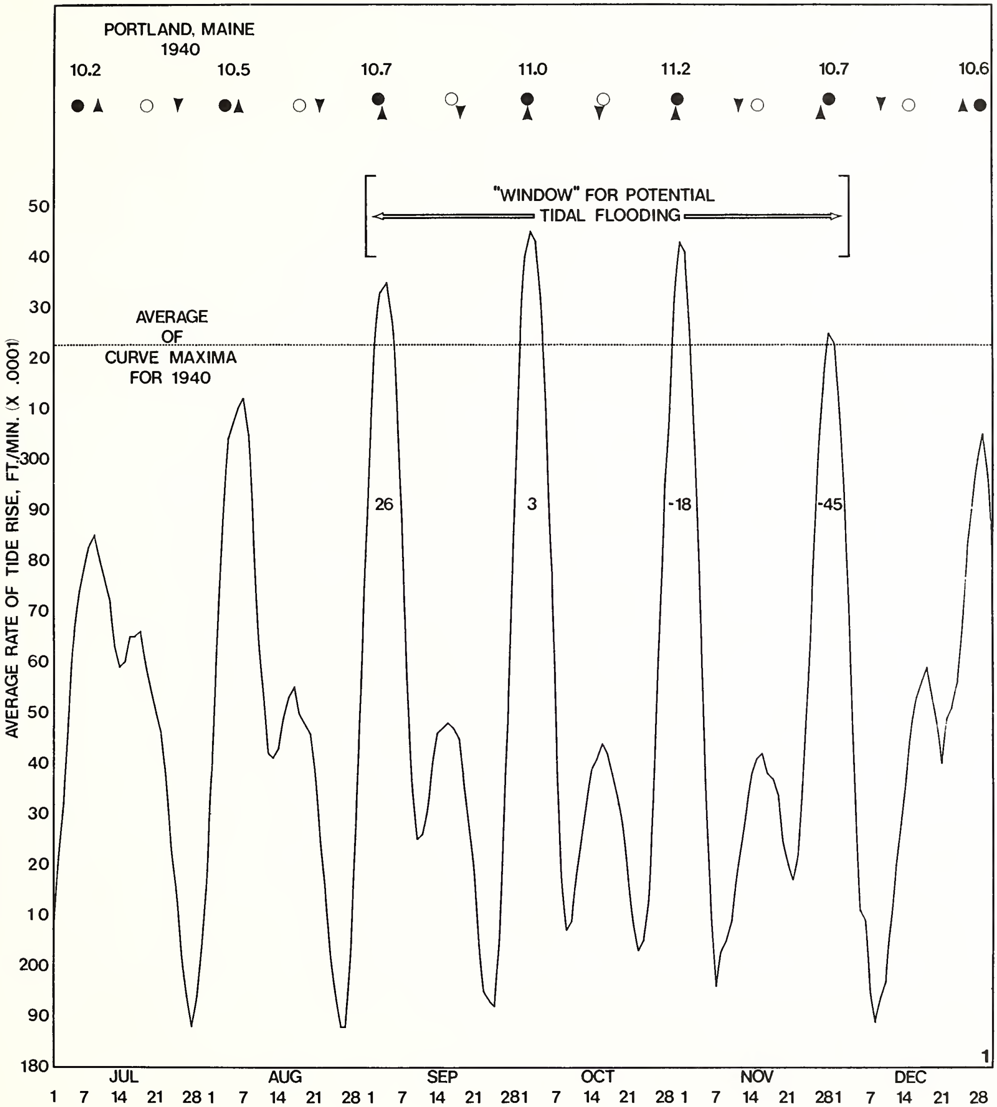


FIGURE 155a.

G-69 (b)



PORTLAND, MAINE
1940
10.2
10.5
10.7
11.0
11.2
10.7
10.6
"WINDOW" FOR POTENTIAL
TIDAL FLOODING
AVERAGE
OF
CURVE MAXIMA
FOR 1940
26
3
-18
-45
1
AVERAGE RATE OF TIDE RISE, FT./MIN. (X .0001)
50
40
30
20
10
300
90
80
70
60
50
40
30
20
10
200
90
180
JUL
AUG
SEP
OCT
NOV
DEC
1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28

H-72 (a)

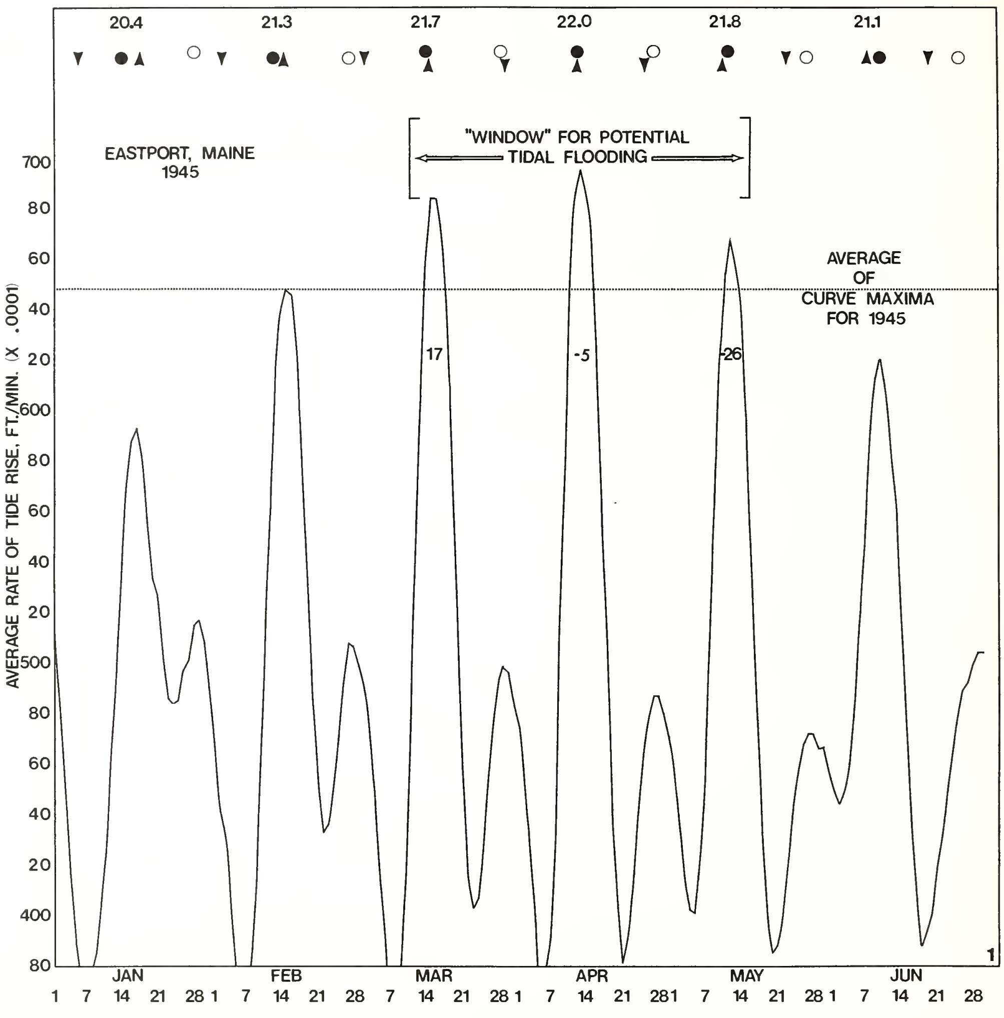


Figure 156a.

H-72 (b)

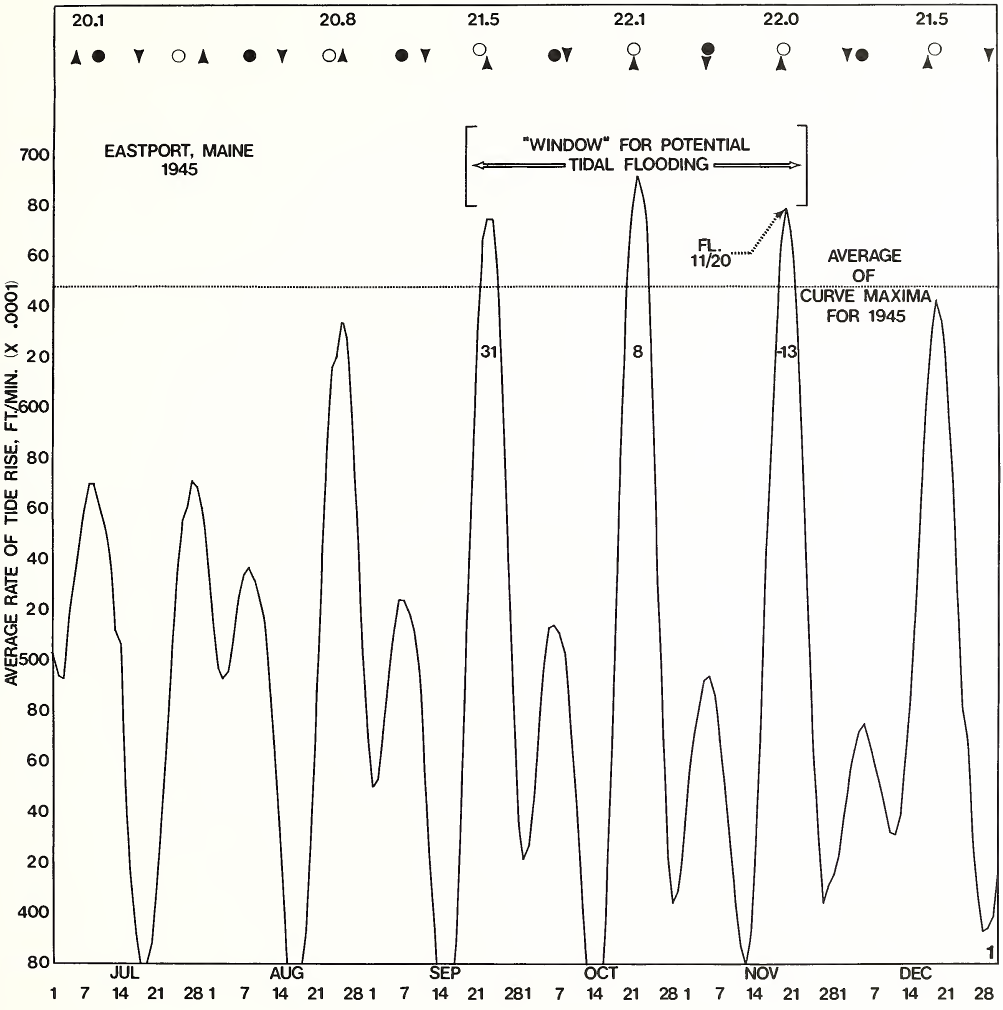


FIGURE 156b.

M-98 e

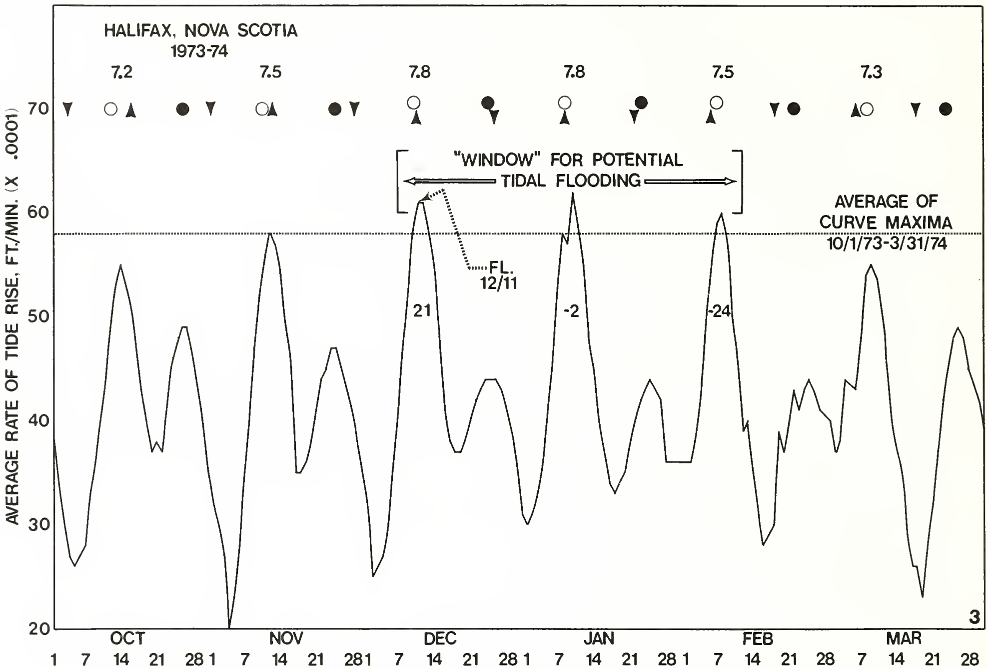


FIGURE 157.

M-98 w

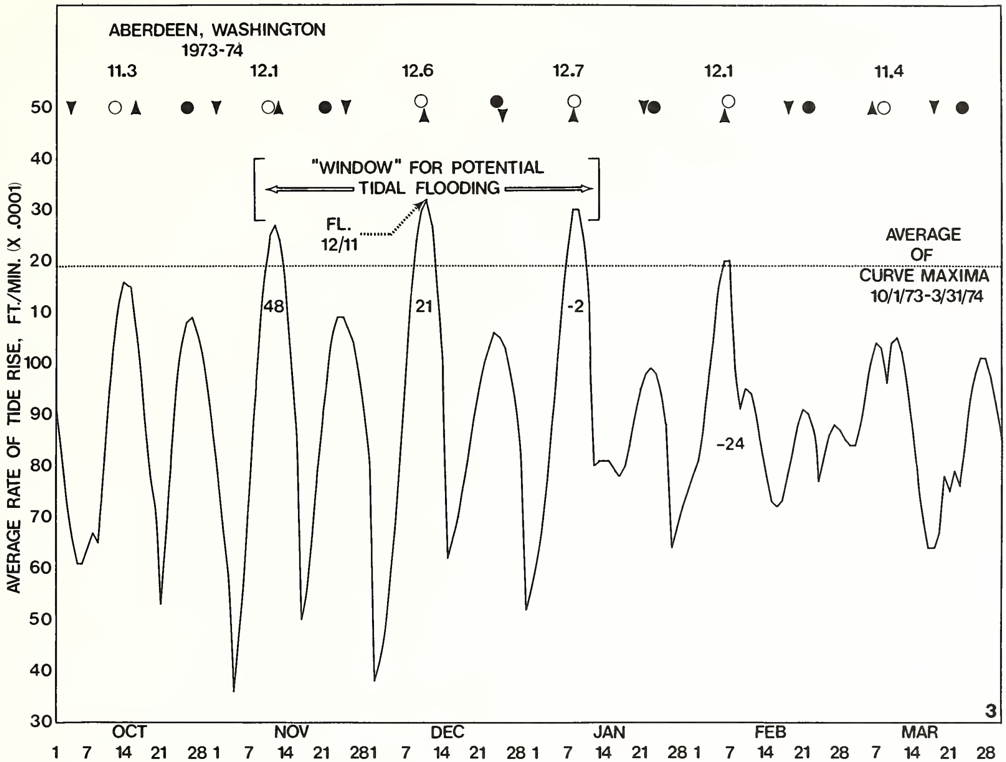


Figure 158.

D–57 (a), E–58 (a)

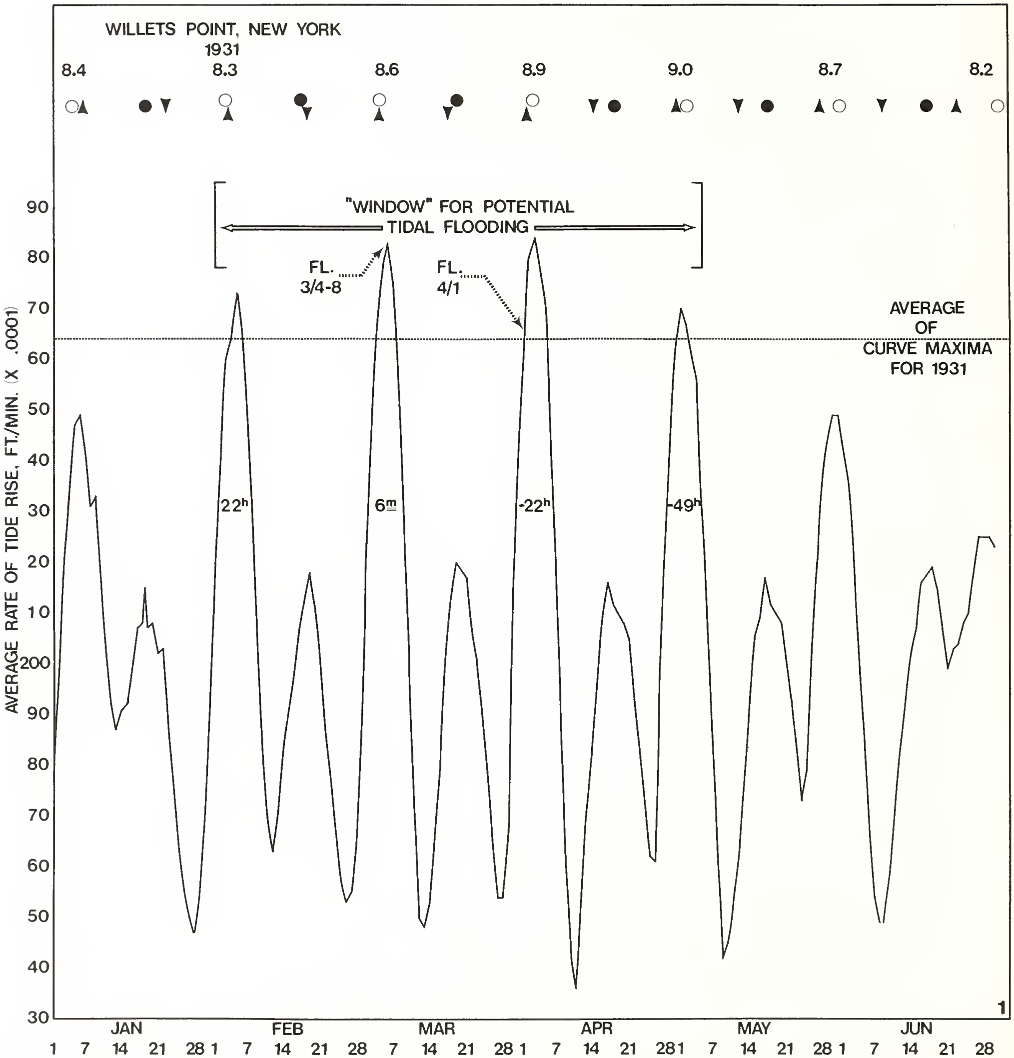


FIGURE 159a.

D–57 (b), E–58 (b)

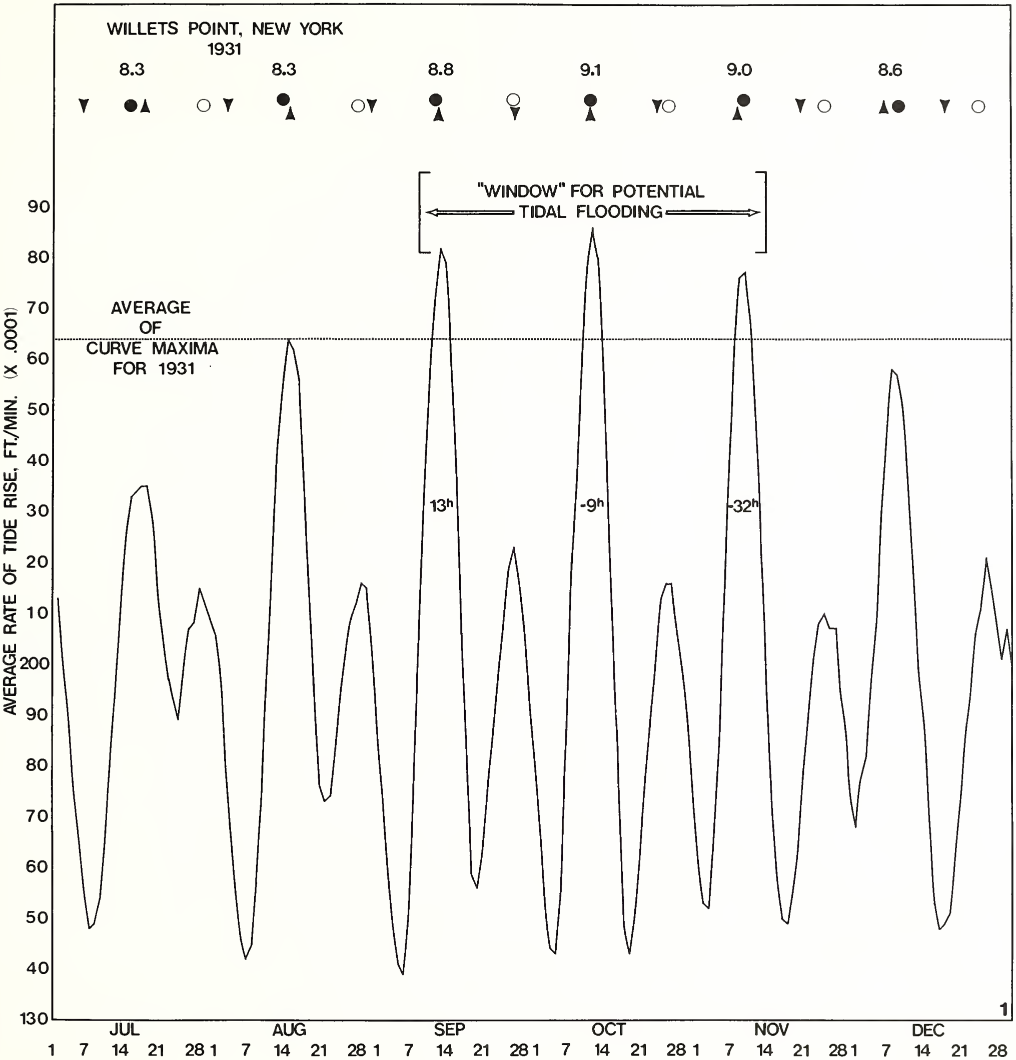


FIGURE 159b.

I–83e (a)

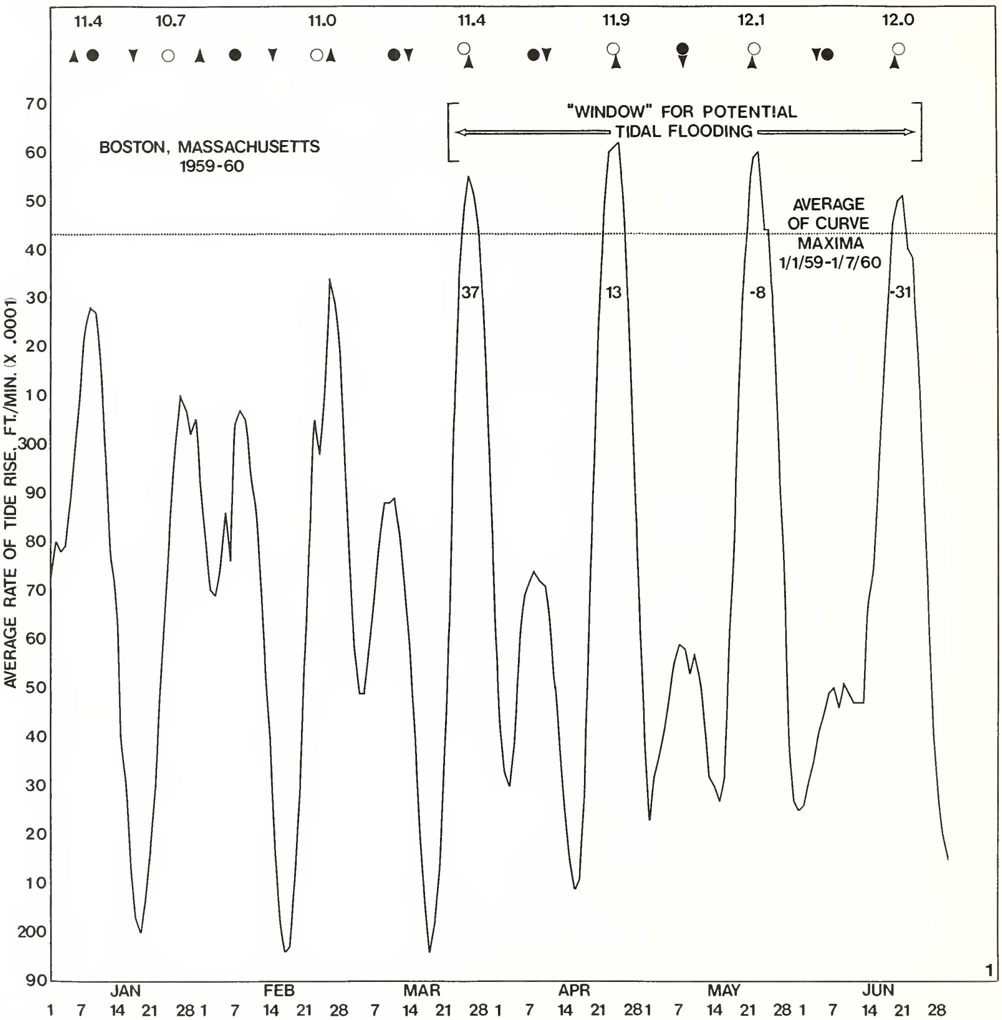


Figure 160a.

I–83e (b)

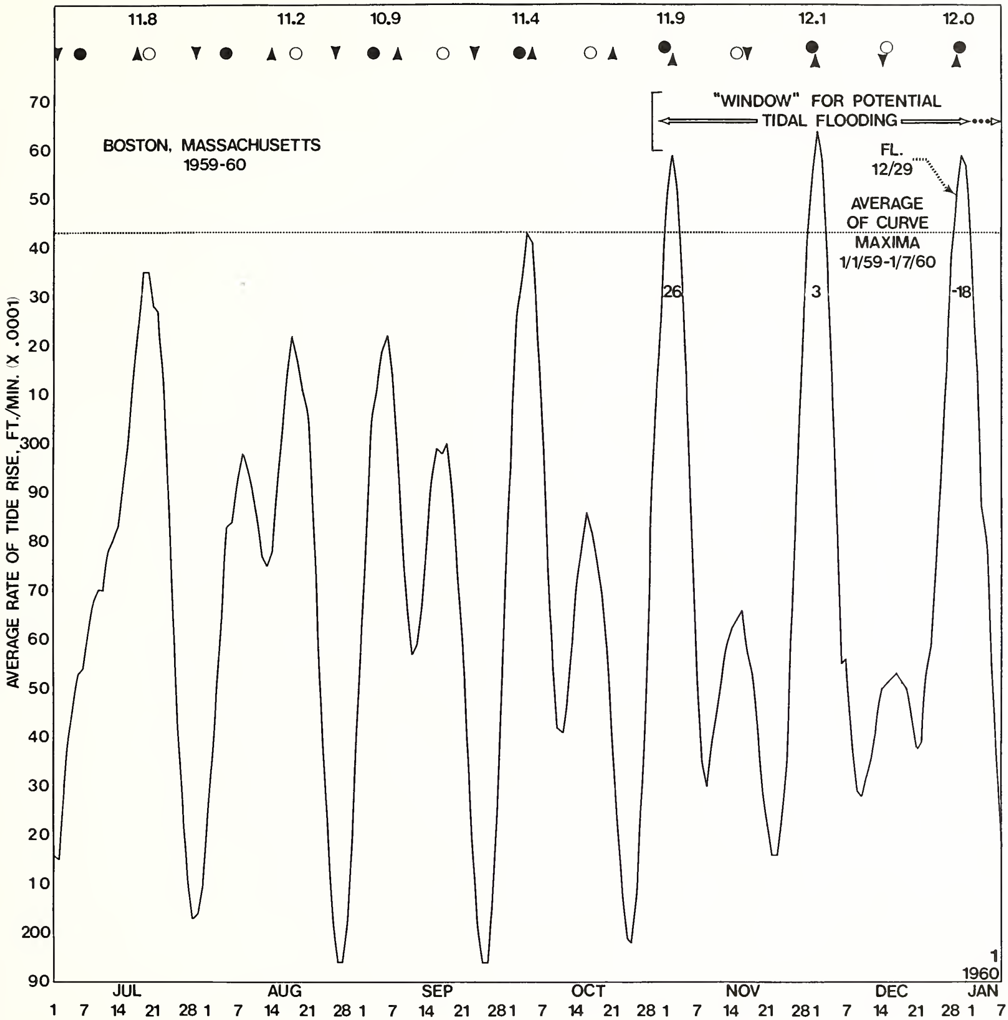


FIGURE 160b.

J–85 (a), K–87 (a)

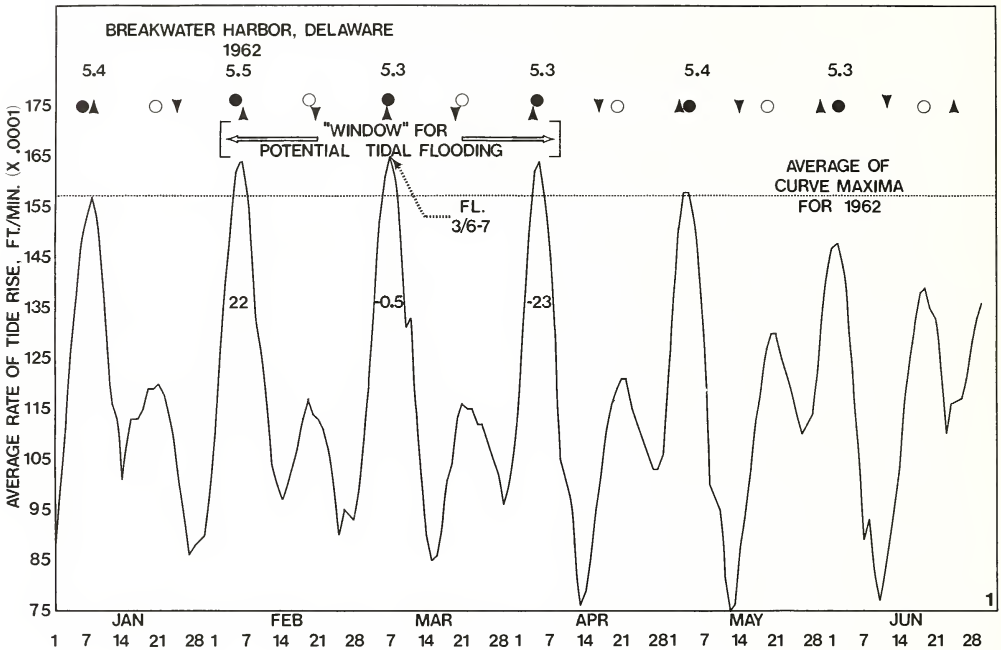


Figure 161a.

J–85 (b), K–87 (b)

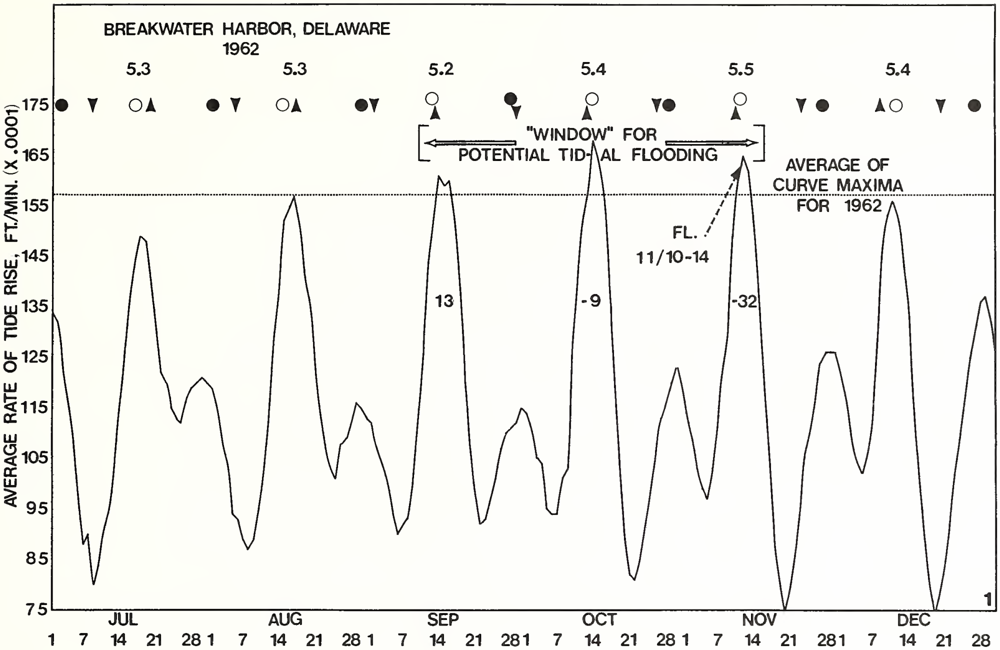


FIGURE 161b.

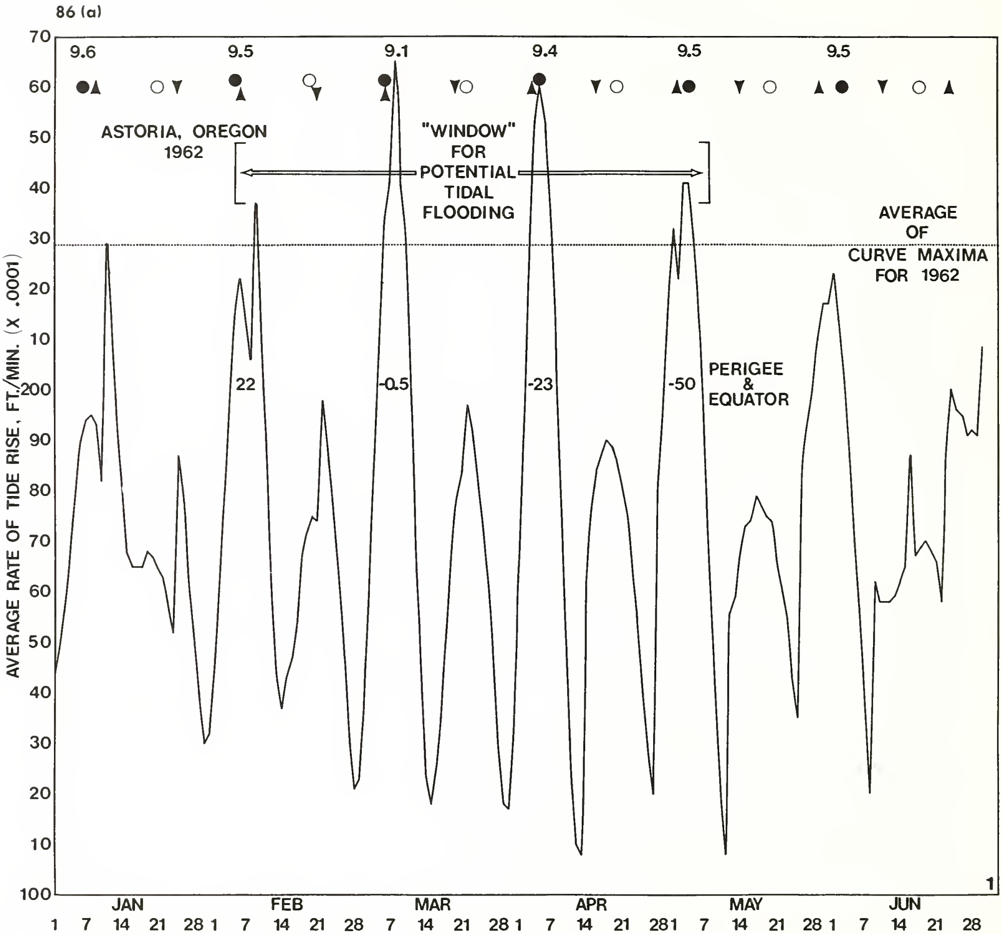

86 (a)
ASTORIA, OREGON
1962
"WINDOW"
FOR
POTENTIAL
TIDAL
FLOODING
AVERAGE
OF
CURVE MAXIMA
FOR 1962
PERIGEE
&
EQUATOR
AVERAGE RATE OF TIDE RISE, FT./MIN. (X .0001)
9.6
9.5
9.1
9.4
9.5
9.5
22
-0.5
-23
-50
JAN
FEB
MAR
APR
MAY
JUN

Figure 162a.

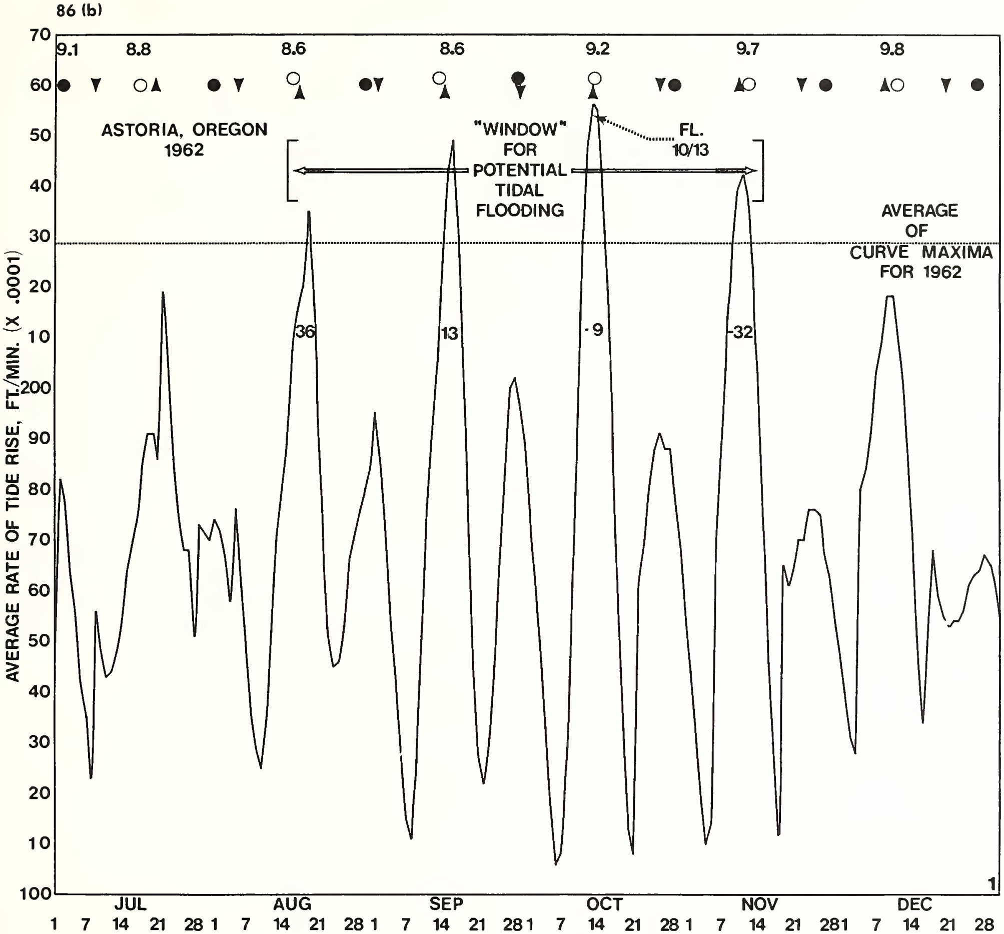

86 (b)
9.1
8.8
8.6
8.6
9.2
9.7
9.8
ASTORIA, OREGON
1962
"WINDOW"
FOR
POTENTIAL
TIDAL
FLOODING
FL.
10/13
AVERAGE
OF
CURVE MAXIMA
FOR 1962
36
13
9
32
AVERAGE RATE OF TIDE RISE, FT./MIN. (X .0001)
70
60
50
40
30
20
10
200
90
80
70
60
50
40
30
20
10
100
JUL
AUG
SEP
OCT
NOV
DEC
1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28 1 7 14 21 28
1

FIGURE 162b.

N–99 (a)

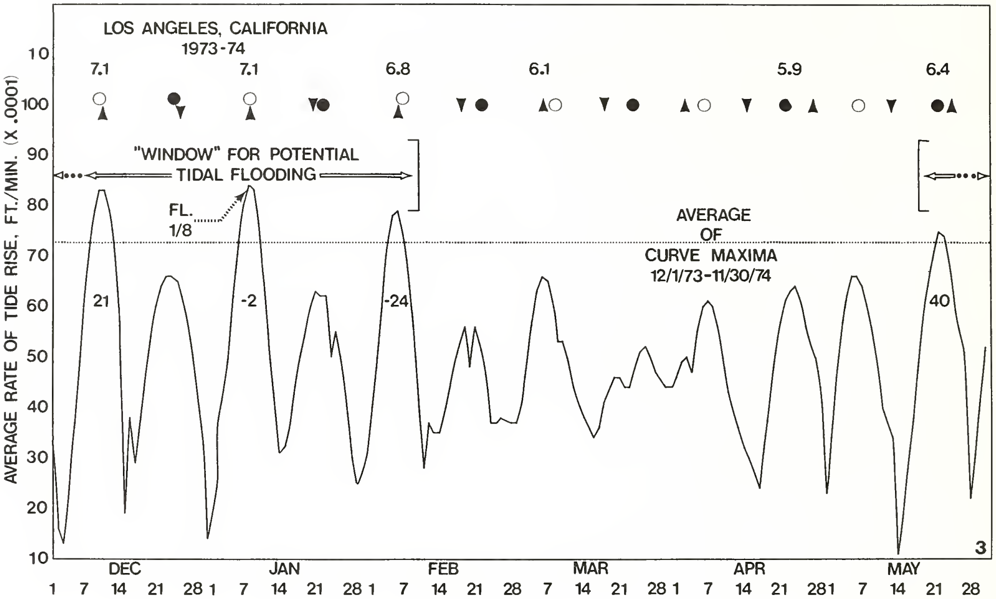


FIGURE 163a.

N–99 (b)

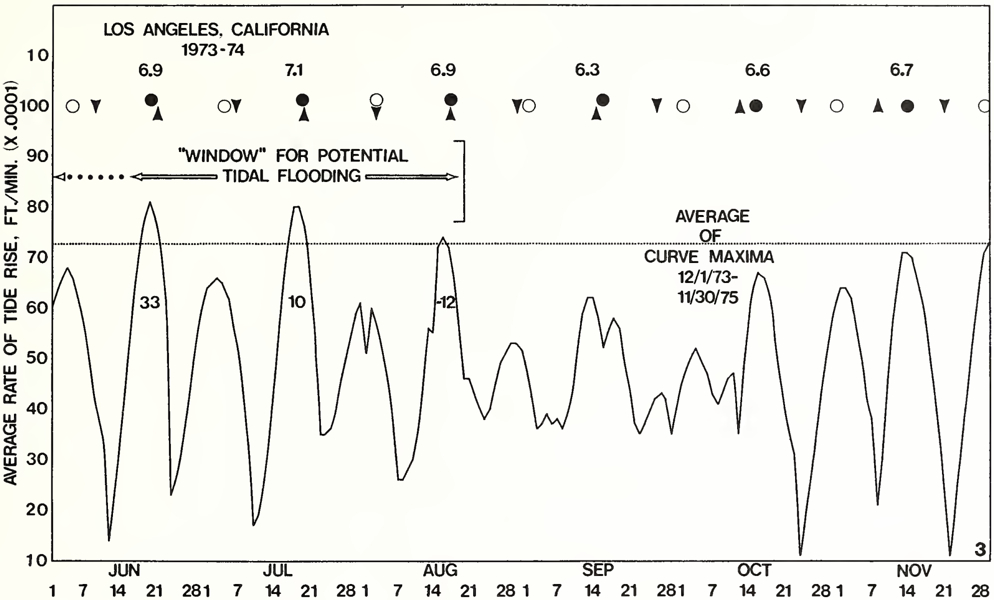


Figure 163b.

nomical tide growth at the times of 16 representative cases of tidal flooding, plotted from such data. Where direct tidal predictions are not customarily made at the location of the tidal flooding, the nearest standard (reference) tide-prediction station has been chosen. The growth rates on the ordinate axis are given in ft/min ($\times 0.0001$). The abscissa axis represents calendar dates, labeled at 7-day intervals. The average of the curve maxima for one lunar year is obtained by dividing the sum of the values for the 13 peaks by 13 lunar months. Across the top of each chart is indicated the height, in feet and tenths, of the highest tide in each calendar month.

The symbols used on each chart are again those coded at the bottom of fig. 153a and are inserted directly above the appropriate dates. Thus, a close alignment of perigee-syzygy is indicated by the symbol of a new or full moon resting centrally on the narrow tip of the perigee symbol. A condition of apogee-syzygy is denoted by either of these lunar symbols located within the upturned cup of the apogee symbol. As one of the lunar-phase symbols and the perigee symbol draw further apart along a horizontal axis, the corresponding astronomical configuration changes from a proxigee- or perigee-syzygy alignment to the situation described earlier as pseudo-perigee-syzygy. Finally (as either the new or full moon becomes separated by its maximum angular distance from perigee), a condition of ordinary syzygy (or spring tides) results.

The plus or minus values located inside the highest of the curve peaks indicate the separation-intervals, in hours, between the time of occurrence of the two phenomena involved—in the algebraic sense perigee minus syzygy.

To provide a totally representative basis for comparison, all of the data being evaluated at any given tidal station are plotted for an entire lunar year of 13 lunations (resulting, in some cases, in an overlapping of successive calendar years).

Those immediately adjacent curve peaks which protrude appreciably above the average line are, in keeping with the context of the present investigation, bracketed and labeled cumulatively as a "window for potential tidal flooding." At times corresponding to the highest points of each of the peaks within these bracketed intervals, the tide is rising the most rapidly (the lower peak in each pair is, of course, automatically excluded). It will be observed that, among all the examples plotted, these "windows" of potential tidal flooding contain not only all of the highest peaks indicating maximum rate of tide rise within the lunar year, but all cases of proxigee-syzygy, perigee-syzygy, and some cases of pseudo-perigee-syzygy.

With one or two exceptions made to avoid repetition and conserve space, both of the "windows" in each year containing close perigee-syzygy alignments are included, for completeness, among the examples of figs. 153–163, irrespective of the half-year in which tidal flooding actually occurred. It is quite obvious, however, that the observed tidal flooding was associated, in every single example represented, with the peak of a curve located within one of these "windows," and hence with a situation of perigee-syzygy having a large $\Delta\omega$-syzygy coefficient. The flooding event did not, in every case, coincide with the *highest* peak in a "window," nor, in every case, with the absolute peak of the curve. But, without exception, the coastal inundation occurred near the time of one of these peaks.

The reason that (despite repeat cases later to be noted) tidal flooding did not occur at the other peaks in the "window" is, of course, the fact that no supporting strong, persistent, onshore winds were present at these times. From the standpoint of the unusually high astronomical tide generated, the conditions present at these times were entirely favorable to coastal flooding, but lacked the necessary associated meteorological factors.

On the other hand, realistic support is given to the premise that such tidal flooding situations are a definite function of perigean spring tides when accompanied by the previously noted conditions of winds through a consideration of the following facts:

(a) At Newport, R.I., in 1927, extreme tidal floodings occurred on both March 3–4 and April 2, one synodic-anomalistic month apart. The same relationship holds true for Willetts Point, N.Y., on 1931 March 4 and April 1 in conjunction with two consecutive occurrences of perigee-syzygy.

(b) On 1933 December 11, in conjunction with a common astronomical alignment of perigee-syzygy, tidal flooding occurred simultaneously on both the east and west coasts of North America—at Halifax, N.S., and Aberdeen, Wash.

(c) Other examples of both of the above types are to be found in table 1, and are appropriately designated in this table.

2. Mixed Tides (Affected by the Diurnal Inequality)

On the west coast of North America, a secondary dynamic factor often intrudes at certain locations to alter the tidal situation typical of the east coast where (with some few exceptions) tides of the semidiurnal type prevail. Diurnal inequality is common at many west coast stations, and mixed tides result.

Along the east coast, the tides are generally characterized by two highs and two lows in each day. Although a higher high water and lower high water as well as a lower low water and higher low water exist, within each pair of high waters and low waters the tides are not extraordinarily different in height. (It must be noted, however, that at very high latitudes the phenomenon of diurnal inequality manifests itself to increase the difference in height between higher high water and lower high water.)

At certain stations on the west coast a tidal situation frequently exists in which, at the Moon's maximum declination, one high water is much higher than the other. This effect, occurring at large southerly or northerly lunar declinations, almost disappears when the Moon crosses the Equator. (See, for example, the general tide curves for Los Angeles in fig. 164.) For those tide stations especially subject to the influence of diurnal inequality, therefore, when the Moon is located at a high declination at time of perigee-syzygy, allowance must be made for this phenomenon. In taking the previously noted differences between the times and heights of LLW and HHW in order to plot the curves of rate of tide rise, a slight modification in procedure is necessary. Instead of subtracting from the height of HHW (or the time thereof) the value for the low water immediately preceding it, the corresponding value for the low water three entries back is used.

This "three-back" method reduces the discrepancy encountered if the method for semidiurnal tides is used, and more accurately assures the representation of a period of water level rise from lowest minimum to highest maximum in accordance with the above-mentioned principles. Not all west coast stations require this adjustment, but those strongly subject to diurnal inequality (e.g., Los Angeles, Calif.; Aberdeen, Wash.) definitely do. Some high-latitude stations on the east coast (e.g., Halifax) also require this special method of solution at times when the lunar declination is large.

Among the examples of this type included in the accompanying group of rate-of-tide-rise curves, those cases using the "three-back" method (figs. 157, 158, 163) are indicated by a boldface number 3 in the lower right corner of the chart. Examples using the "one-back" method are similarly identified by a number 1. Figures 153–163 contain 11 examples of both types, covering the broad range of coastal locations previously noted.

It has been indicated that such rapid and extreme rates of tide rise are present and demonstrable only where the type of tide involved is one affected strongly by the Moon. In this respect, three further considerations are noteworthy in connection with the foregoing analysis aimed at establishing a positive correlation between perigean (or proxigean) spring tides, accelerated rate of tide rise, and astronomical tidal flooding potential. These items are by way of qualification on the previous discussion:

(a) Between 1885 and 1911, only 19 harmonic constituents were used in the computation and prediction of tides by the U.S. Coast and Geodetic Survey. These did not include the 3 second-order semidiurnal and diurnal constituents, the 2 smaller elliptic terms (semidiurnal and diurnal), the larger evectional diurnal term, the tridiurnal constituent, and 3 overtide constituents, and included only 1 component in each case among 5 dealing with compound tides and 5 representative of long-period tides. (See fig. 43). The 18 additional components were introduced and first became a part of the harmonic solutions forming the basis for the tide tables published in 1912. Accordingly, the use of the previously described method for determination of rate of tide growth (which is sensitive to a greater level of accuracy) is not entirely effective when the tide data were published prior to this year.

(b) Sufficiently large mean spring ranges must be present at the stations utilized in such computations to indicate a characteristic responsiveness to lunar influences and a corresponding rapid rate of tidal buildup. From a large variety of tidal growth curves plotted for both the east and west coasts, it is apparent that those tide stations whose mean spring range is less than 5 feet do not lend themselves readily to this test analysis. By the same token, however, such coastal locations are not strongly prone to tidal flooding at times of perigee-syzygy.

(c) The determination of astronomical tidal flooding potential by the above methods (employing the closely corresponding $\Delta\omega$-syzygy coefficient) is, of course, not possible for tides which are more responsive to solar than lunar influences.

An Independent Check on the Validity of the $\Delta\omega$-Syzygy Coefficient

Since first proposing the use of the $\Delta\omega$-syzygy coefficient as an indicator of vulnerability to tidal flooding conditions, it has been left to substantiate that the daily rate of lunar motion in right ascension—the secondary element of the $\Delta\omega$-syzygy coefficient—is itself a parameter accurately representative of tidal flooding potential.

In the immediately preceding section, the conditions of predicted and actual flooding have been positively correlated with the accelerated rate of tide rise associated

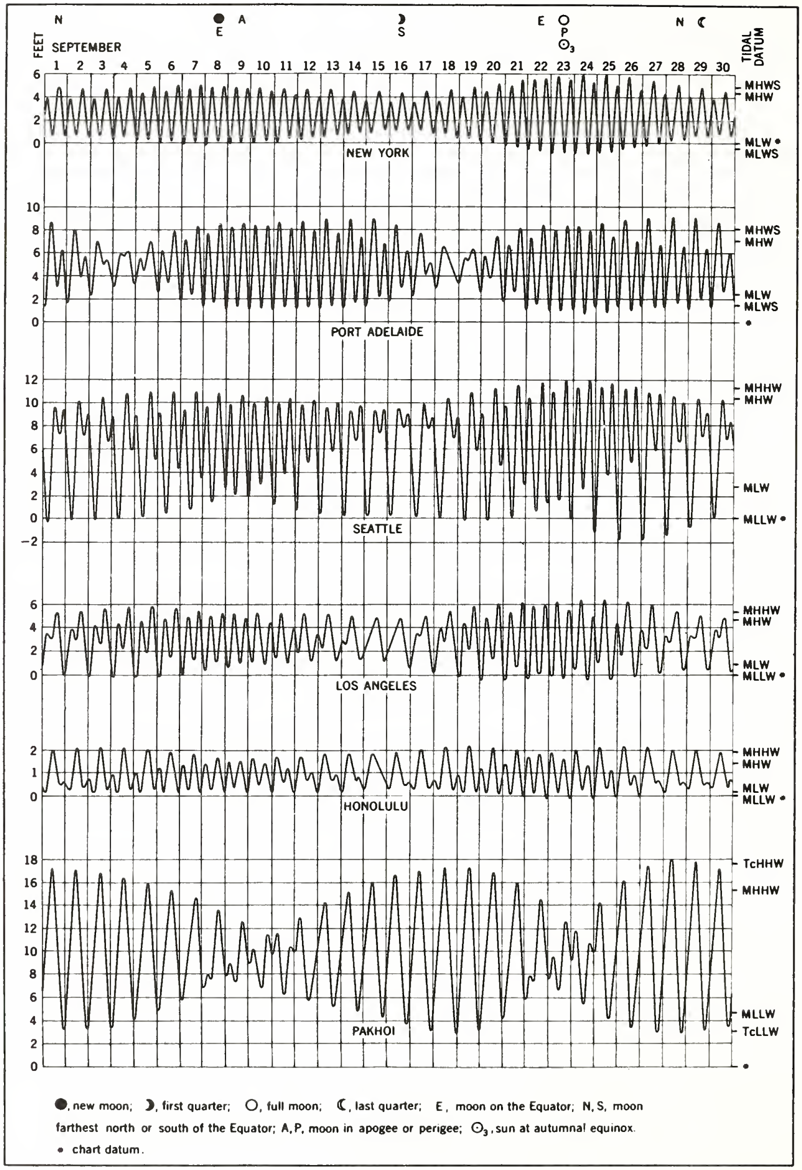


FIGURE 164.—Representative daily tidal curves of different types (see p. 298 and fig. 6 in appendix) at selected stations throughout the world. Note the individual, varying effects of the perigee-syzygy alignment (plus proximity to the autumnal equinox) on September 23.

with perigee-syzygy. To complete the circle of analysis, it is finally necessary to demonstrate that the unusually rapid rate of tide rise at times of perigee-syzygy can be directly correlated with the daily velocity (and hence change of position) of the Moon in right ascension. Such an analysis can be accomplished by the use of figs. 165a and 165b.

These diagrams, in their inherent nature, constitute a parallel reconstruction of the tide curves contained in figs. 161a–161b, which represent the varying daily rate of tide rise thoughout the year 1962. However, for comparative purposes, these curves are plotted entirely from astronomical data in *The American Ephemeris and Nautical Almanac* and are, therefore, independent of any particular tidal stations. The ordinate values and curve amplitudes accordingly will not change from tide station to tide station as in the rate-of-tide-rise curves, but the properties of the purely astronomically derived curves can prove to be very meaningful in relationship to the tide curves. Figs. 165a–165b represent graphs of daily lunar motion in right ascension plotted with declination as ordinate against the time as abscissa (indicated to exactly the same scale as that previously used). For correlation purposes, the present curves may be directly compared with the matching curves of figs. 161a–161b, plotted completely from tide table data.

Specifically, the ordinate axis in these present figures represents the angular distance in right ascension through which the Moon appears to move on each day of the year in consequence of both real and apparent motions. The movement is expressed as a difference between the Moon's position in right ascension at 0^h of date and its position at a time 24 hours earlier. The tabular differences calculated from *The American Ephemeris and Nautical Almanac* are converted uniformly to minutes of time. The final reduction takes into account corrections for lunar declination ($1/\cos^2 \delta$) and for the effects of the Earth's diurnal rotation. The result is, therefore, the projection on the celestial equator of the apparent daily motion of the Moon.

The horizontal dotted line labeled "Average of Curve Maxima for 1962" is obtained by taking the mean of the ordinate values for all peaks throughout a 13-month period and dividing by 13.

The effect of acceleration of the Moon's apparent motion in right ascension in increasing the length of the tidal day at times of perigee-syzygy is clearly manifest in the fact that the peaks of the curves extend perceptibly above the average line at these exact times.

A further salient factor is the very exact correlation between the portions of these curves protruding above the line in figs. 165a and 165b, and the matching extreme peaks in figs. 161a and 161b. The even greater significance of this circumstance is that, whereas the first curves are plotted entirely from astronomical tables and the second from tide tables, the profiles of the respective curves are an almost identical match for all dates throughout the year. The close resemblance between the positions, shapes, and augmented amplitudes of the curves at times of perigee-syzygy is particularly noteworthy. Since the lunar phase relationships do not directly affect the Moon's daily motion in right ascension as they do sensibly affect the tides, figs. 165a and 165b do not contain the series of dual maxima (one of which is elevated) and minima shown in figs. 161a and 161b.

Finally, an item of major importance should be mentioned in connection with the search for a suitable coefficient of tidal flooding. Throughout the entire series of curves representing a considerable variety of tide stations in figs. 153–163, the only major tidal flooding events observed among the 56 years of record covered, occurred at one of the peaks extending above the respective "average of curve maxima" lines.

As an aid to the determination of astronomical conditions which are especially conducive to tidal flooding when they exist concurrently with strong, persistent, onshore winds, all examples of perigean spring tides occurring between 1977 and 1999 in which the perigee-syzygy separation-interval is ≤ 24 hours are summarized in table 34. Those cases of proxigee-syzygy and extreme proxigee-syzygy leading to the production of exceptionally high tides, and thus particularly vulnerable to severe coastal flooding when supported by the correct meteorological conditions, are identified for quick reference.

Summary and Conclusions

In summary, the following facts have been made evident throughout the preceding chapters:

A. The Tidal Aspects of Perigee-Syzygy Alignment

1. The coincidence of perigean spring tides and strong, persistent, onshore winds must inevitably result in active coastal flooding, a statement amply confirmed by table 1. By contrast, perigean spring tides alone, without supporting winds, are usually insufficient of their own right to cause major flooding. (See table 27.) Because of this required combination of events, at no time has the word "prediction" of tidal flooding been used in this publication. The astronomically induced tides can be computed for thousands of years into the future with extreme precision.

J–85 (a)

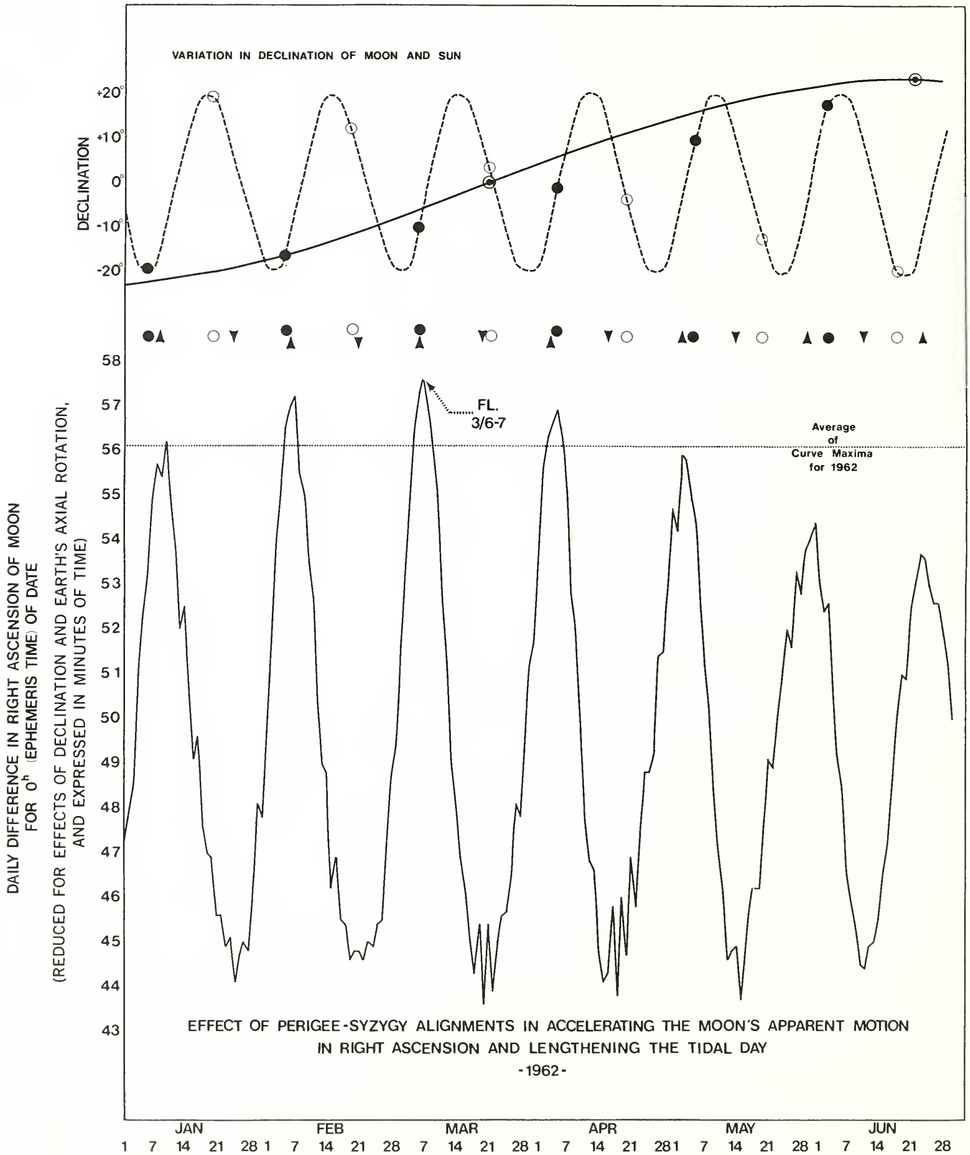


FIGURE 165a.—(Discussed in text.)

J–85 (b)

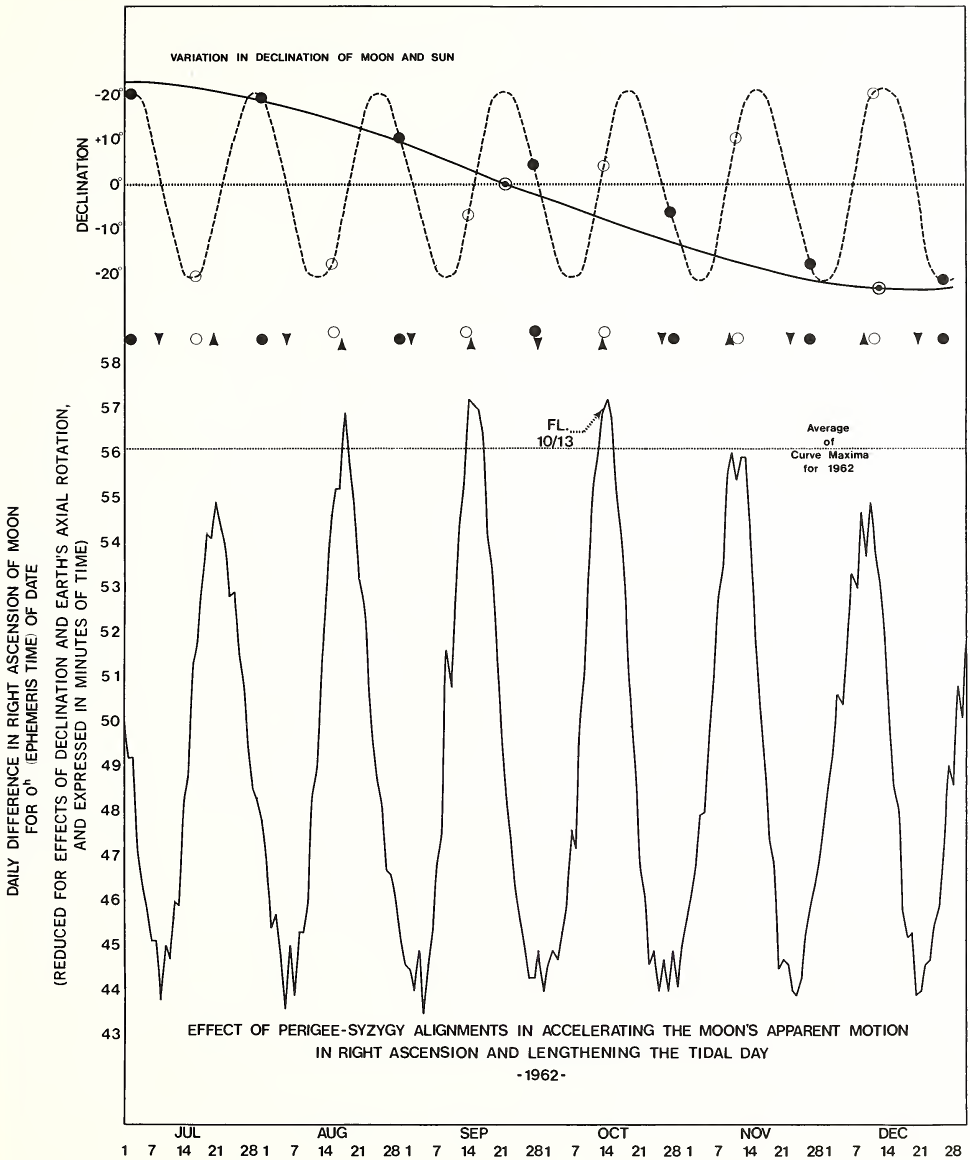


Figure 165b.—(Discussed in text.)

TABLE 34. —*A Checklist of the Central Dates (Mean Epochs) of Perigean Spring Tides* ($P-S \leq \pm 24^h$) *Occurring Between 1977 and 1999*
[Proxigean spring tides are indicated by the letters "Pr." before the date, and extreme proxigean spring tides by the letters "Ext. Pr." See table 16 for full astronomical details.]

	Mean epoch of perigee-syzygy			Perigee minus syzygy		Mean epoch of perigee-syzygy			Perigee minus syzygy
	Year	Date	Hour (e.s.t.)	(h)		Year	Date	Hour (e.s.t.)	(h)
	1977	5/3	1600	(+16)		1988	2/17	0730	(−7)
	1977	6/1	1300	(−6)		1988	8/27	0900	(+6)
Pr.	1977	12/10	1530	(+5)		1988	9/25	0630	(−15)
	1978	1/8	1500	(−16)		1989	3/7	2000	(+14)
	1978	6/20	2330	(+15)		1989	4/5	1830	(−9)
	1978	7/19	1700	(−5)	Pr.	1989	10/14	1830	(+5)
Pr.	1979	1/28	0300	(+4)		1989	11/12	1700	(−16)
	1979	2/26	0230	(−19)		1990	4/25	0530	(+13)
	1979	8/8	0600	(+16)		1990	5/24	0230	(−9)
	1979	9/6	0300	(−6)	Ext. Pr.	1990	12/2	0430	(+3)
	1980	2/16	1600	(+24)		1990	12/31	0430	(−19)
	1980	3/16	1430	(+1)		1991	6/12	1300	(+12)
	1980	4/14	1230	(−21)		1991	7/11	0930	(−9)
	1980	9/24	1430	(+15)		1991	12/21	1700	(+24)
Pr	1980	10/23	1230	(−7)	Ext. Pr.	1992	1/19	1630	(+1)
	1981	4/5	0230	(+23)		1992	2/17	1600	(−22)
	1981	5/3	2330	(+1)		1992	7/29	2100	(+12)
	1981	6/1	2000	(−22)		1992	8/27	1730	(−9)
	1981	11/12	0030	(+13)		1993	2/7	5000	(+20)
Pr.	1981	12/10	2330	(−9)	Ext. Pr.	1993	3/8	0400	(−2)
	1982	5/23	1100	(+22)		1993	4/6	0200	(−24)
	1982	6/21	0700	(0)		1993	9/16	0400	(+12)
	1982	7/20	0300	(−22)		1993	10/15	0200	(−10)
	1982	12/30	1200	(+10)		1994	3/27	1530	(+19)
	1983	1/28	1130	(−11)		1994	4/25	1330	(−3)
	1983	7/10	1800	(+22)		1994	11/3	1400	(+10)
	1983	8/8	1430	(+1)		1994	12/2	1300	(−12)
	1983	9/7	1100	(−22)		1995	5/15	0100	(+18)
Pr.	1984	2/17	0000	(+8)		1995	6/12	2130	(−3)
	1984	3/16	2230	(−13)	Pr.	1995	12/22	0100	(+8)
	1984	8/27	0100	(+22)		1996	1/20	0100	(−14)
	1984	9/24	2200	(0)		1996	7/1	0800	(+18)
	1984	10/23	2000	(−22)		1996	7/30	0430	(−3)
	1985	4/5	1000	(+6)	Pr.	1997	2/7	1300	(+6)
	1985	5/4	0730	(−15)		1997	3/8	1200	(−16)
	1985	10/14	1000	(+20)		1997	8/18	1500	(+18)
Pr.	1985	11/12	0830	(−1)		1997	9/16	1230	(−3)
	1985	12/11	0800	(−24)		1998	3/28	0000	(+4)
	1986	5/23	1900	(+6)		1998	4/25	2200	(−18)
	1986	6/21	1530	(−15)		1998	10/5	2330	(+17)
	1986	12/1	2100	(+18)	Pr.	1998	11/3	2200	(−14)
Pr.	1986	12/30	2000	(−4)		1999	5/15	0830	(+3)
	1987	7/11	0200	(+6)		1999	6/13	0500	(−18)
	1987	8/8	2130	(−15)		1999	11/23	0930	(+15)
	1988	1/19	0800	(+16)	Pr.	1999	12/22	0930	(−7)

However, sea-surface winds—especially under the most changeable offshore storm conditions, and with only ship weather reports and weather satellite photographs as guides—can rarely be accurately predicted more than several days in advance.

Major tidal flooding is dependent upon such supporting wind action as well as the coexistence of high tides (in the cases being investigated, further heightened by the influence of perigee-syzygy alignment). Accordingly, carefully chosen phrases indicative of this astronomical situation as "enhancing the dynamic potential for," or "increasing the vulnerability of the shoreline to ," severe tidal flooding in the presence of strong onshore winds have been used. Severe erosion of the coastline in low, sandy regions is an attendant factor in any situation involving the simultaneous occurrence of intensified onshore winds and astronomically heightened tides.

2. Hurricane winds in combination with any state of the tide are usually intense enough to cause coastal flooding. However, to a degree which is variable with the distance of the hurricane's center from the coastline, the strength of the storm (i.e., the existing pressure gradient), the actual wind velocities present, their angle-of-attack to the shoreline, the duration of their movement over the water, the time of a hurricane's landfall with respect to high water, and the daily range of the tides at the location in question, the severity of the flooding may vary over a wide range.

Disregarding for the moment the high- and low-water extremes produced by perigean spring tides, a hurricane entering the coastline at low tide—although causing extreme wind damage—will not cause as severe flooding as one impacting the coastline at high tide. A landfalling hurricane will likewise, during any period of average tidal range, cause much more severe flooding than an offshore hurricane.

In the case of an offshore hurricane, the duration of onshore surface wind movement is not usually as long as that associated with an offshore winter storm, because of the generally far more rapid forward movement of the hurricane in its recurving path at higher latitudes. An overwater, deep low pressure system of extratropical nature, accompanied by strong onshore winds, may be totally blocked by the presence of a stationary high-pressure system and the winds may thus persist in onshore movement, creating a long overwater *fetch*. Because of the great kinetic energy contained within a hurricane, it is rarely so blocked, and rather than coming to a complete standstill, is only diverted in its path, split into components, or barometrically filled and weakened in intensity by the blocking high pressure center.

On the other hand, in the case of the coincidence of a hurricane with perigean spring tides, the extra rise in the high water level accompanying this type of tide acts as an astronomically produced setup condition, and provides a factor of consequence in the production of extreme coastal flooding.

In recapitulation, cases of record show that, when landfalling hurricanes have arrived on the coast at times of low water—or even in conjunction with moderately high tides—the *principal* damage sustained frequently is wind damage. The coincidence or near-coincidence of hurricanes and perigean spring tides inevitably have resulted in extreme coastal flooding (see table 2). Interestingly, although the range of tides at Galveston, Tex., is not sufficiently large to support a major astronomical height-inducing influence at perigee-syzygy, the great historical tidal flooding associated with the hurricane of September 8, 1900 at Galveston, which drowned some 6,000 persons, occurred on the same day as a perigee-syzygy alignment ($P-S=14^h$).

3. The coincidence of strong, persistent, onshore winds with *ordinary* spring tides can cause major beach erosion and seawall damage if the winds are sufficiently strong and occur very close to the times of high water. Unless the velocity of the surface winds is high and the path of their onshore movement is long-continued over the water, the magnitude of coastal flooding produced is, however, never as large as that created by the same circumstances of strong onshore winds, plus perigean spring tides.[b]

A considerable increase in tide-raising power occurs when the Moon reaches a position at or near perigee, because of the proximity of the Moon to the Earth. However, for true perigean tides to occur, with the least reinforcement from the gravitational attraction of the Sun, they must be produced with the Moon at one of its quadrature positions (first or third quarter) when the gravitational forces of the Moon and Sun are opposed. The additional tide-raising force at lunar perigee, although contributory in enhancing the tides, is not as effective when thus acting alone as when a simultaneous perigee-syzygy alignment occurs. If strong onshore winds coexist with a high phase of the tides produced at times of perigee-quadrature, some minor flooding may result, but the principal damage is that created by wind and associated high waves directly along the coast, without strong flooding inland. [Cf., for example, the instance of the coastal storm of February 11–12, 1973 at Nags Head, N.C., and vicinity described in *Mariners Weather Log*, vol. 17 (May 1973), pp. 188–189.] Theoretical analysis indicates that wind-induced coastal waves of the breaking type are raised to

[b] Pseudo-perigean spring tides, at their upper limit of perigee-syzygy separation ($\pm 84^h$), also merge rather indistinguishably into ordinary spring tides. A major destruction to seawalls and the piles supporting beach homes and patios occurred at Malibu Beach, Calif., during the pseudo-perigean spring tides ($P-S=-82^h$) of 1978 March 3–7. This occurrence was the third in a series of such destructive tides following upon the two already discussed at the end of chapter 7. But the immediate and subsequent attritional damage by pounding, wind-driven surf piled on top of moderately above-average spring tides was not accompanied by significant tidal flooding.

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greater heights the more intense is the wind action and, somewhat anomalously, the shorter the duration of storm growth and period of wave rise [Cf., Geoffrey L. Holland, "Effect of the Rate of Storm Growth on Subsequent Surge Elevation," *Journal Fisheries Research Board of Canada, 26,* (8), 1969, pp. 2223–2227]. The frictional coupling action between the wind and the sea surface is also greater, the steeper is the windward slope of the waves produced. [See also the bibliography, category (18).]

4. Yet another coastal flooding influence of considerable consequence is the combination of perigean spring tides with hydrological runoff from near-coastal uplands. This circumstance may cause severe flooding of coastal regions as the result of an impairment of normal river or drainage runoff to the sea during a period of unusually high tides. The increased water levels produced at times of perigee-syzygy may provide such an effective barrier to hydrological runoff and force the rising waters to flood over the banks of rivers or drainage channels leading to the sea.

The necessarily intense initial watershed drainage is, of course, created by the melting of thick layers of snow and ice at higher elevations, by heavy and sustained precipitation, and by the especially rapid and unimpeded runoff of water from slopes denuded by strip logging and mining. Freshets and flash floods are the result. Aqueducts, storm sewers, and natural feeder channels sufficient to take care of ordinary drainage situations may, under such conditions, prove entirely inadequate to accommodate the intense runoff which, in encountering the rising tide, is caused to back up into gutters and streets [Cf., table 5, key no. 79(2) col. 2]. This is especially true if the perigean spring tides, lifted further by strong onshore winds, rise to the actual height of the outlets which comprise the sewer and drainage outfalls to the sea, thus physically preventing the effluent discharge. Significantly, however, an effective blocking action of extreme hydrological runoff can occur as the result of perigean spring tides alone, without the coincidence of strong onshore winds, provided in this same respect that intense and persistent offshore winds do not prevail.

Proper awareness should be observed by climatologists to any coincidence between years of heavy snowfall and years of proxigean tides (as defined earlier in this volume), and attention should be given by hydrologists to the possibility of runoff from snowmelt or heavy precipitation on upland slopes coinciding with periods of perigean spring tides. A correlation between simultaneously rapidly increasing readings on river gages and tide gages can provide an appropriate short-range warning.

5. Important practical and environmental influences of perigean spring tides, even without the support of strong onshore winds, include their action in: (1) bringing saltwater farther up estuaries, thus modifying or even destroying the equilibrium conditions required by various forms of marine fauna and flora (the destruction of birds' nests in saltwater marshes or seacoast wildfowl sanctuaries also may result from the insurging water); (2) hastening the breakup of river ice in consequence of their strong associated currents; and (3) facilitating navigation through coastal shoals and over rivermouth bars. All these factors are well substantiated by examples cited in chapters 2–3. Other miscellaneous influences, both adverse and utilitarian, have been suggested in these same chapters and are further amplified below.

B. The Subsidiary Effects of Extreme High and Low Waters and Strong Tidal Currents at Times of Perigee-Syzygy

Several practical but—because of the complex accompanying circumstances—not always directly provable consequences of perigean spring tides will next be considered.

Among these are: (a) the possible contributions of the extreme low-water phase of such tides to instances of ship grounding; (b) the increased chance of ship collisions imposed by the strong currents associated with such tides; and (c) the effects of the accompanying extreme high and low waters and intense tidal currents upon marine life in the intertidal zone.

The same gravitational forces responsible for unusually high waters in conjunction with perigean spring tides also produce extremely low waters at the opposite tidal phase. There is no question but that an inherent danger exists in regard to ship grounding at such times of excessive low waters. This is especially true since the actual water level is then considerably below the levels of mean low water or mean lower low water on which chart datums (in the United States) are based. Closer inshore, in the tidewater belt, entire schools of fish also can be left stranded by the unusually low water.

Because of the large number of possible alternative reasons for ship groundings, such as pilot's or navigator's error, adverse weather, failure of navigation equipment, mechanical breakdown of the engines or rudder, confusion of warning signals, etc., it is manifestly implausible to designate this critically reduced low water as more than a possible contributing cause in any one accident. The number of shipmasters' claims to "water level being lower than anticipated" mentioned in a footnote in chapter 3 as a reason for the respective grounding casualties is, however, too sizable to ignore. The overriding factor for consideration is that, even aside from these numerous direct attributions of grounding due to unexpectedly low water, such circumstances do provide a special hazard for deep-draft and only slowly maneuverable supertankers. The likelihood for accompanying oilspills, with serious damage to the coastline and the natural environment, cannot be emphasized too strongly.

A contiguous navigational threat to the same large, cumbersome ships consequent upon the existence of perigean spring tides lies in the much stronger tidal current flows which must necessarily accompany such tides. It is an incontrovertible fact that these unwieldy craft will be subject to increased navigation problems under the aforementioned conditions, particularly when the vessels are underway in narrow coastal rivers or channels where the currents are running even more strongly and there is little room for maneuvering. Should sudden course-correcting movements be required as the result of confused signals, improperly identified targets, misinterpreted orders, or poor visibility, the danger that this action will not be accomplished in time is directly increased. Collisions may result. Actual examples of such tidal influences follow:

REPRESENTATIVE INSTANCES OF SHIP GROUNDINGS IN SHALLOW DEPTHS PRODUCED AT THE LOW-WATER PHASE OF PERIGEAN SPRING TIDES

Ship groundings due to sudden encounter with unusually shallow water depths naturally occurred more frequently in earlier times when vessels—many still under sail—lacked the quick response of engine power and engine-steering control. This early navigational deficiency, while not carried over into present day ship dynamics is, however, in certain respects replaced by the ponderousness, large moments of inertia, and correspondingly reduced maneuverability of modern supertankers and other deep-draft vessels.

Among the following representative examples of ship groundings, instances have been chosen in which a direct correlation is possible with the phase of the tides at the time of the grounding.

Although strong surface winds and/or impaired visibility may also prevail during the times of ship groundings, these meteorological conditions taken together with the extremely low tides present simply complete a triad of mutually contributing causes to such accidents. [If the winds are offshore, they may depress the tides still further; if onshore, they may raise the tides, but at the same time force an unsteerable ship shoreward toward the danger area of the astronomically lowered tides.]

In all of the examples cited below, either an astronomically induced extreme low water or strong tidal currents (or both) were present at the time of the disaster. To what degree these factors might have contributed to each accident is a matter of open conjecture—as in all cases of this type where possible multiple causes exist. In keeping with any such partially uncertain evaluation in this work, the only rational answer is that "under such tide and current conditions, a greatly increased potential for danger is present, and proportionately increased safety measures should, in consequence, be observed."

Two outstanding historical cases of ships running aground subject to the circumstance of especially low water associated with perigean spring tides are contained in appropriate New York City newspaper articles for June 3, 1871 and February 10, 1895 as abstracted below:

". . . On June 3, 1871 . . . the ship *Pacific* [bound from Glasgow to New York] . . . went aground off Southhampton, Long Island . . . 1,000 tons of pig iron which was her cargo was thrown overboard, after which she floated again . . ."

A very close perigee-syzygy alignment ($P-S=-1^h$) occurred on this same date, having a mean epoch of 1871 June 3, 0130^h 75°W.-meridian time. The resulting greatly depressed tidal waters at low-water phase and associated strong tidal currents were accompanied by a stiff surface wind. In the news article, this wind—because of its more obvious effects—was mistakedly given as the cause of the very low (ebb) tide and strong currents. This supposition totally ignores the facts, later indicated in this same article, that both the flood and ebb currents (incoming and outgoing) were very intense at their respective times, without the wind having shifted through 180°. Continuing with the news article:

"Yesterday [6/3] . . . a low ebb tide resulted from the gale, and it was impossible for the ferryboats to cross river in a direct course . . . so strong was the tide in the middle of the stream . . ."

(*New York Evening Post,* June 7, 1871, p. 4, col. 8)

It was subject to these treacherous tide and tidal current conditions that the *Pacific* grounded at Southhampton.

* * * * *

Similarly, during the low-water phase on February 9, 1895, tides occurred which the *New York Times* described in a headline (see table 5, key No. 25) as the "lowest tide in twenty years." This extremely low tide was produced by a perigee-syzygy alignment having a mean epoch of 1895 February 9 at 1000^h e.s.t.—together with a northwest wind.

The *New York Times* further relates:

"Sandy Hook, N.J., Feb. 9—The large four-masted steamship *Patria* of the Hamburg-American Packet Steamship Company, while proceeding to sea this evening, grounded in the main ship channel, [!] near the southern edge of Palestine Shoal . . ."

(*New York Times,* February 10, 1895, p. 1, cols. 3, 7)

Since high water occurred at 7:47 p.m., e.s.t. at New York (Governors Island) on February 9, 1895, this case of grounding probably was contributed to more by the strong currents than by the unusually low tide situation associated with perigee-syzygy.

* * * * *

Dense fog or heavy precipitation combined with the low-water phase of perigean spring tides also can provide a particularly hazardous combination for a ship. Drifting off course by virtue of reduced visibility, the vessel may come unexpectedly into waters of unusually shallow depth. Among representative examples of ship groundings known definitely to have occurred during the low-water phase of perigean spring tides (although other factors may be attributable) are those of:

March 13, 1918

". . . The steamship *Kersaw* with 121 passengers and four crew ran aground early yesterday [morning] [3/13] . . . the steamship was bound from Boston to Philadelphia, and cause of the accident was that the Captain lost his bearings. When aground, the *Kersaw* was between the inner and outer bars . . ."

(*New York Herald,* March 14, 1918, p. 2, col. 1)

"Easthampton, L.I., Mar. 13—The Merchant and Miner's Liner *Kersaw* with 117 naval reservists aboard as well as other passengers struck a sandbar during a heavy fog last night [actually, very early in the morning] and is still held fast . . . Fortunately, the weather was calm and practically no sea was running when the accident occurred . . . [the vessel] apparently lost her way in the fog . . . the ship had strained her plates badly when she struck the bar and all idea of pulling her out this [late morning or evening] high tide was abandoned . . . *Kersaw* lies just inside the outer bar on the beach . . . Leaks are being fixed in time for her to float out at next high tide . . . *Kersaw* displaces 2,600 tons and is 224 feet long."

(*New York Tribune,* March 14, 1918, p. 14, col. 1)

[The predicted lower low water at New London, Conn., on March 13, 1918 was at 3:35 a.m., e.s.t.; the mean epoch of perigee-syzygy was 1918 March 12, 1600^h e.s.t., $P-S=+2^h$.]

* * * * *

1930 February 15

". . . Inbound with 45 passengers and crew of 65, the liner *Admiral Benson* went aground at 6:40 p.m. Saturday [2/15] near the mouth of the Columbia River . . . Black fog hampered the movements of the rescue craft and made it extremely difficult for them to locate the liner . . ."

(*Oregon Sunday Journal,* February 16, 1930, p. 1, col. 8)

". . . Cause of the wreck will not be known until official investigation . . . thus far it remains a mystery to those on shore and not even plausible conjectures seemed to have been advanced . . . The mouth of the Columbia River is a wide and safe entrance, guarded by navigation aids of all kinds . . . Lightship southwest of entrance in line with the first channel, lights day and night, with lights visible 11 miles . . . this vessel is in good shape . . . it has submarine signal devices, foghorn, and radio compass equipment . . . Beyond the jetty markings there are whistles, [and] slightly north of North Head, flashing lights, everything marked and signaled . . . *Benson* went on in the fog, just why remains to be seen . . ."

(*Oregon Daily Journal,* February 17, 1930, p. 1, cols. 7, 8)

[The predicted lower low water at Astoria, Oreg., on February 15, 1930 was at 9:28 p.m., P.s.t. (higher high water had occurred at 2:58 p.m., and the tide was falling); the mean epoch of perigee-syzygy was 1930 February 12, 1500^h P.s.t., $P-S=-20^h$.]

* * * * *

Despite all that has been said in previous pages of this work concerning the advantage offered by perigean spring tides in facilitating the passage of ships over sandbars and through inshore shoals and shallows, a word of caution must be sounded where modern deep-draft vessels (especially those subject to underway "squat") are involved. It must be clearly emphasized from a safety standpoint that the high-water phase of perigean spring tides does not provide a navigational panacea for easing modern supertankers or other deep-draft bulkcarriers into ports or harbors around which reefs and sandbars exist.

A typical case in point is illustrated by the grounding of the oil-carrying supertanker *Lake Palourde* (of 125,831 deadweight tons) just inside Los Angeles (San Pedro) Harbor on November 20, 1976. This date marked the beginning of a period of perigean spring tides, and came just prior to a perigee-syzygy alignment having a mean epoch of 1976 November 21, 0030^h P.s.t. ($P-S=-13^h$).

Quoting from the *Los Angeles Herald-Examiner* for November 21 (p. 1, col. 1):

"A 974-foot long supertanker loaded with 880,000 barrels of crude oil has run aground just inside the Los Angeles Harbor in San Pedro and immediate action was begun to free the vessel and guard against a potentially disastrous oil spill.

The *Lake Palourde* . . . became locked in the sand at dawn yesterday while [enroute] . . . to port . . ."

As noted, grounding occurred "at dawn." Sunrise for this latitude and date occurred about 6:38 a.m. The ship obviously was trying to take advantage of the extra high tide afforded by the perigee-syzygy alignment. At Los Angeles Outer Harbor, this morning's higher high water was predicted to reach its crest of 6.9 ft above the datum of mean lower low water at 7:23 a.m. on this date. The tidal range (from LLW to HHW) on this date was 8.1 ft, which, subject to the action of the perigean spring tides, is 2.7 ft greater than the diurnal range of 5.4 ft (from MLLW to MHHW) at this location. The predicted height of 6.5 ft is also 1.1 ft above the value of mean higher high water at Los Angeles Harbor, based on a 19-year period of observations.

However, as the events attest, even this appreciable tidal rise at time of perigee springs is often inadequate to accommodate ships of such unusually large draft over shallow ocean bottoms.

Tidal currents probably played no major role in the grounding of this vessel, in spite of their usual acceleration at times of perigee-syzygy. As noted in the National Ocean Survey's *Tidal Current Tables, Pacific Coast of North America and Asia—1976,* p. 203: "In Los Angeles and Long Beach Harbors the tidal current is weak. It is reported, however, that three minute surge waves are responsible for major ship movements and damage." No surface winds sufficient to cause strong surges were present at the time of this grounding.

REPRESENTATIVE INSTANCES OF THE EFFECTS OF STRONG CURRENT FLOW ASSOCIATED WITH PERIODS OF PERIGEAN SPRING TIDES

A perigee-syzygy alignment having a separation-interval of only -8^h occurred at 2300 (e.s.t.) on February 3, 1939. Although the winds were not right to cause tidal flooding on this date, the influence of the astronomical alignment in producing strong tidal currents is indicated by the following excerpts from the *New York Times* of February 4 (p. 20, col. 3):

". . . The Cunard White Star liner *Aquitania,* due to dock at 8 a.m., was not made fast until 3:10 p.m. because of an extremely strong ebb tide running at 7 miles an hour that held her at the pier head and carried away 4 wire hawsers . . ." [With total objectivity in mind, the already strong, astronomically induced current might also have been added to, in a meteorological sense, by preceding heavy rains, possible runoff from snowmelt on the mountains, and prevailing northwest winds. Were any of these conditions indeed contributory, this is still exactly the kind of situation in which special precautionary measures should be observed. Seriously aggravated circumstances can be created when such factors coincide with perigean spring tides and/or the augmented tidal currents produced during the same period (although generally not exactly coincident in time with, the maximized tides).]

Again, as reported in the *New York Times* on the following day, February 5 (p. 7, col. 2):

"Passenger liners sailed from North River pier yesterday with 4,000 passengers . . . The first to leave at 11 a.m. was the French liner *De Grasse* for the West Indies—followed at 11:30 a.m. by the *Conte di Savoia,* which was supposed to be on a slackwater. She moved out from a pier at W. 52nd St.—the tide got her and she started downstream broadside with 5 tugboats to prevent her hitting the end of the next pier, where the *Aquitania* was berthed. Three liners sailed at 5 p.m. . . . the *Aquitania* which lost seven hours in docking Friday [2/3] because of the strong ebb tide . . . lost another six hours yesterday [2/4] and left at 6 p.m. instead of noon . . ."

EXTREME TIDE AND CURRENT IMPACT ON OFFSHORE PLATFORMS IN SHALLOW OCEAN AREAS

The further potential danger to offshore oil rigs implanted on the ocean floor with foundations at depths at which tidal currents are still strong should not be overlooked. Erosion and weakening of the base of support by such strong tidal currents at the same time that the surface platform is being battered by strong winds and storm surges may cause an oscillating action of the entire structure which, through resonance, may work toward its final collapse. Whatever the ultimate cause, it should not be ignored that the destruction of an Air Force's radar tower located 80 miles off the mid-Atlantic coast on January 14, 1961 occurred on the same day as perigean spring tides which caused active coastal flooding in New Jersey. At this same time, strong subsurface currents were present and—at the surface—intense overwater winds. [Descriptions of the elaborate oceanographic engineering measures designed to protect a proposed nuclear-powered electric generating plant in a planned location 3 mi off Great Bay, N.J.—and simultaneously to safeguard the coastal environment—are contained in: Public Service Electric and Gas Company, *Atlantic Generating Station, Units 1 and 2*—Preliminary Site Description Report, vols. 1–2. (Cf., especially, vol. 1, pp. 2.2–5, 2.2–6 for storm tide effects.)]

INFLUENCE OF PERIGEAN SPRING TIDES UPON THE ECOLOGY OF THE COASTAL ZONE

In connection with the dynamic effects of perigean spring tides, their associated strengthened currents, and the possibility for the production of active storm surges when these heightened tides are accompanied by strong, persistent, onshore winds, there must be mentioned the further aspect of potential ecological damage to the coastal environment.

Among appropriate considerations are the upstream intrusion of saltwater far beyond the usual boundary of saline mixing, and saltwater penetration into freshwater ponds or pools consequent upon wind-blown storm surges and severe tidal flooding. Both of these actions are made physically possible by the existence of perigean spring tides.

The first-mentioned expansion of the semidiurnal saltwater intrusions may modify estuarine circulation and flushing patterns, result in a temporary but recurring diversion of freshwater bound downstream toward coastal estuarine destinations, and upset the usual chemical, physical, and biological exchange relationships with the freshwater runoff. The latter storm-surge effects also may be accompanied by the destruction of wildlife habitats, nests, and rookeries.

Actions taken to offset these detrimental changes may, in themselves, be deleterious to the coastal environment. For example, the construction of seawalls, dikes, and breakwaters to prevent tidal flooding, and barriers to prevent salinity intrusion, may, in turn, exert an ecological influence. Many of the ramifications of such manmade changes are discussed in the publication series: U.S. Department of the Interior, Fish and Wildlife Service, *National Estuary Study,* vols. 1–7, Washington, D.C. 1970. [Cf., especially, vol. 2, pp. 1–39; vol. 4, pp. 1–16.] These factors need not, therefore, be repeated here. References to certain other matters of ecological import which can be specifically affected by perigean spring tides are given in paragraph 10 of the summary listing following section D, in succeeding pages.

C. Unproven Geophysical Relationships With the Phenomenon of Perigee-Syzygy

Thirdly, there are certain events of geophysical nature whose seemingly plausible associations with the alignment of perigee-syzygy must be better substantiated before any correlation can be scientifically accepted. As has happened in the case of the many suggested nonphysical attributions to sunspots, one of the most common unscientific actions perpetrated is to attribute observed phenomena to opportune physical causes simply because a time-coincidence between apparent cause and adduced effect exists between them. The lay literature all too frequently abounds with such efforts to establish possible causal connections between two factors based upon their coexistence in time, or apparent repetition in cycles. Such imagined relationships involve a severe contravention of the principles of scientific method, since almost any two complex and comprehensive sets of data can—subject to sufficient degrees of freedom—be made to show some individual correlations, if the right combinations of parameters are chosen. There is neither intention nor desire in the present work indiscriminately to amass various possible factors which might conceivably be affected by increased lunisolar gravitational influences.

However, scientific method dictates that an impartial and open mind be maintained toward any rationally established, empirically verifiable factor of causality. It further prescribes that no deductively or inductively derived, hypothetical causal relationship which is supported by a reliable body of evidence, be rejected until it fails completely under a sufficient number of analytic tests. Because such tests for acceptance are both rigorous and comprehensive, there is insufficient space in the concluding pages of this work to more than list a few such potential relationships under various degrees of scientific investigation. Although each of these unquestionably requires further and broader evaluation, all are of a caliber of seriousness sufficient to warrant mention in terms of the possible additional test grounds afforded by perigean spring tides. No one case is to be regarded as any more than speculative at the present stage of research.

1. Wholly Conjectural Relationships Between Meteorological Factors and Perigee-Syzygy

Statistically considered, a more than random number of cases of major tidal flooding exists involving a coincidence between perigean spring tides and the presence of strong onshore coastal winds which are a necessary contribution to tidal flooding. Among these are frequent instances of such flooding: (1) spaced one synodic-anomalistic month apart; (2) joined in interrelated sets of 1 and either 6.5 or 7.5 periods of 29.5 days (see chapter 6 for explanation); (3) bridged in exact long-term multiples of these same periods; and, perhaps most significantly, (4) which have occurred simultaneously on both the east and west coasts of North America. (See table 1.) These circumstances lead logically to the academic question: Is there any possible situation resulting from the extra gravitational forces produced by the alignment of Sun and Moon at ordinary syzygy—and particularly the additional forces created at perigee-syzygy—which, in known meteorological theory, could have an effect upon inducing, reinforcing, or sustaining strong surface wind movements? More particularly, are there any induced meteorological effects resulting from the enhanced gravitational forces at perigee-syzygy and capable of producing the very winds which, acting upon the perigean spring tides coincidentally raised, in turn create tidal flooding?

In considering these questions, one closely relevant factor which must not be overlooked is the statistical probability of a simultaneous combination of the following events, considered as a meteorological circumstance only: That (1) a sufficiently deep, intense, atmospheric low pressure system (2) will be in exactly the right position close offshore (3) with wind movement directed onshore toward a vulnerable lowland portion of the coast; (4) such winds having blown over the water for a sufficient length of time to establish a long fetch and (5) having attained a sustained maximum velocity precisely within one of the few periods of several days in each year in which perigean spring tides reach their peak (6) coincidently with the short interval of a few hours corresponding to one or both of the daily high water phases of the tides.

At this point in time, there seems to be no known physical mechanism relating lunisolar gravitational force and barometric fluctuations except those same forces which cause the very small tides detectable in the Earth's atmosphere. (See section 3, below.) If some parameter were present relating such external gravitational influences and dynamic convergence in the atmosphere—the latter factor being that creating low pressure systems and the associated steep barometric gradients responsible for strong winds—some more positive connection might be assumed.

A considerable amount of research is underway covering possible relationships between the tidal forces created at various lunisolar configurations (those consequent upon the phase of the Moon) and the observed amount of atmospheric cloudiness and precipitation [see bibliography, category (33)]. Further statistical correlations with the Moon being simultaneously at perigee [1] and the lunar node have been detected. Such research might ultimately also lead to a possible association between lunar influence and those offshore storms, accompanied by winds, which contribute to coastal flooding at times of perigean spring tides. From many years of record, an above-average frequency of cloudiness has been observed at times of full moon. Regions of cloudiness are, almost without exception, represented by regions of convergence and low atmospheric pressure, which are also accompanied by strong winds. Any effect of the reduced parallax and increased gravitational force of the Moon on the Earth's atmosphere at times of perigee-syzygy is, however, opposed by the converse necessity—if any such augmented cloudiness relationship holds true—for a statistical increase in clear skies at time of apogee, a circumstance which is not discernible among the records.

The entire question of some possible meaningful correlation between the full phase of the Moon and precipitation factors, if real, is a challenging one deserving of further attention and should be rigorously investigated. By analogy with the qualification previously imposed, necessitating a decrease in cloudiness at apogee, if a connection between precipitation and full moon does exist (without requiring that the cause be luminosity-related) a matching statistical decrease in precipitation over sublunar regions of the Earth should be noted between full moon and new moon.

2. Other Possible Geophysical Influences

The known geophysical influences the Moon exerts upon ocean tides through enhanced gravitational forces at times of perigee-syzygy leads, in turn, to the possibility of: (a) increased influences upon tides in the solid Earth as a result of these same circumstances; (b) a small increase in the established lunar-induced component of the Earth's external magnetic field.

a. *Potential Connections Between Perigee-Syzygy, Earth Crustal Movement, and Seismic Activity*

The first of the preceding two conjectures also raises the closely related issue whether any role is played by the increased gravitational tide-raising forces at times of perigee-syzygy as a triggering mechanism for earthquakes. The necessary initiation of this action would be provided by earth-tidally induced ancillary stresses on opposite sides of a geological fault plane, of sufficient magnitude to cause shearing and sudden differential slippage along the plane—setting off an earthquake.

Again, any correlative attempts to establish a causal connection between seismic events and the coincidence of perigee-syzygy are marked by many possible pitfalls and uncertain factors such as: (1) the existence of a fault plane whose contiguous faces are already near the rupture point as the result of built-up differential crustal deformations—and along which a jarring dislocation and release of strain would likely have occurred anyway; (2) other factors of dynamic control in dislodgement of the fault-surfaces such as changes in lubrication between the opposing faces, or in rock tensile-strength when strained to the ultimate fracture point; and (3) a triggering action imposed by the mechanical jostling of other small earthquakes or microseisms.

However, the existence of a physical connection between earthquakes and lunar syzygy with its coalignment of lunar and solar gravitational forces has been explored by many reliable scientists, and specific instances of correlation with times of perigee-syzygy also have been cited [see the references following section D, below, and in the bibliography, category (32)]. It must be emphasized that any possible relationships assignable between earthquakes and increased gravitational forces present at ordinary syzygy would be enhanced by the alignment of perigee and syzygy. Accordingly, any promising line of investigation should be comprehensively pursued to give adequate consideration to the latter cases.

The possibility exists that the wide range of lunisolar forces imposed on the Earth throughout the complete half-cycle of lunar positions from perigee-syzygy to apogee-syzygy may result (to whatever small degree) in an alternate compression and resilient expansion of the Earth's ellipsoidal figure. The consequent maximum rate of deformation of the crust at *both* perigee-syzygy and apogee-syzygy could well account for the failure of a large number of major earthquakes to coincide with times of perigee-syzygy alone. The only requirement under this expansion and contraction hypothesis (if any connection with earthquakes exists) would be that earthquakes would occur statistically with greater frequency *within* those anomalistic months which contain perigee-syzygy alignments, since in these months the alternate compression and expansion would be the greatest at perigee and apogee. In any dynamic correlation between lunitidal forces and earthquakes, greater emphasis also should be placed on vertical rather than horizontal tide-raising forces (see *Geotimes, 19,* 30, 1974).

Inertial reaction times for any such gravitationally induced movement of the crust to take place, and corresponding relaxation times for the slightly deformed Earth to recover its figure must also be considered in any such investigation. This factor of indeterminancy for so many types of rock materials again points to the difficulty of establishing a meaningful correlation.

Research in this field has gone forward in a progressive manner and, with equal consideration to opposing opinions, numerous representative examples may be cited. These examples are grouped in a supplemental commentary at the end of section D. Other citations to the scientific literature on this topic are given in the bibliography, categories (26)–(29) and (32).[c]

One final comment is germane in this connection. A rather controversial work was published in 1974.[2] This related to the possibility that a "superconjunction" of all of the planets of the solar system in 1982 might cause devastating earthquakes along the great San Andreas fault rift in California between 1980 and 1984. The earthquake catastrophe would come about, it is stated, by a triggering action induced by the mutual alignment of the planets. The gravitational effects of this alignment are assumed to proceed through a complex series of natural events, involving tidal disturbance and the production of huge sunspots in the solar photosphere, the generation of additional corpuscular streams of high-energy particles, a saturation of the Earth's upper atmosphere thereby, excitation of the motion of large air masses and turbulence, the imposition of an extremely minute but quick-acting deceleration of the Earth's rotation, a resulting deformation of the crust, and the production of the earthquakes. Although this hypothesis is conceived upon tides raised in the Sun by this gravitational alignment, the Moon is at all times the principal tide-raising body in connection with earth tides. Despite the great mass of Jupiter, at even its least distance from the Earth it is still some 1,500 times farther away than the Moon. Since the tide-raising force on the Earth varies inversely as the cube of the distance of the attracting body, the tide-raising force of Jupiter is less than 0.00001 that of the Moon. Likewise, Venus, the closest planet to the Earth, exerts a tide-raising force only about 0.0001 that of the Moon.

Astronomically considered, no instance of maximum proxigee-syzygy alignment—nor even a case of proxigee-syzygy (as both configurations are defined in chapter 7)—occurs during the period 1980 to 1984.

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[c] A pertinent newspaper summation of conflicting scientific opinions with regard to a possible lunar triggering action in connection with the Seattle earthquake of April 13, 1949, was contained on the front page of the *Los Angeles Examiner* for April 15, 1949. The effect was supposed by some seismologists to accompany a lunar eclipse occurring on April 12, without mention of the closer approach of the Moon to the Earth caused by the associated perigee-syzygy alignment. This alignment ($P-S=-20^h$, $\pi_{avr}=61'11.1''$) had a mean epoch of 1949 April 12, 1000^h (P.s.t.). Perhaps more significantly, in terms of a possible alternate, minute compression and expansion of the Earth's crust suggested in the text above as taking place during the succession of a close perigee, a remote apogee, and a second close perigee, the earthquake occurred one anomalistic month after a very close alignment ($P-S=2^h$, $\pi_{avr.}=61'28.2''$) having a mean epoch of 1949 March 14, 1200^h (P.s.t.). At the subsequent and intervening apogee-syzygy, the Moon's apogee distance was correspondingly greater, followed by a close perigee approach again at the April 12 perigee-syzygy alignment.

By contrast, on March 8, 1993, the Moon will reach one of its closest possible approaches to the Earth ($\pi=61'30.0''$). It will then possess a very large $\Delta\omega$-coefficient, and the Sun will be at $\delta=-4.8°$ (close to the plane of the Moon, ($\delta=0.4°$) at a time of maximum proxigee-syzygy. The mean epoch of the event ($P-S=-2^h$) occurs at 0400^h (e.s.t.). Astronomically induced ocean tides, at least, will certainly be very high and susceptible to wind-supported flooding conditions along lowland coastlines of the Earth within several days on either side of this date.

b. *Geomagnetic Fluctuations of Tidal Nature*

Geomagnetic variations of measurable degree are related to the constantly changing gravitational effects associated with the actual and the apparent revolutions of the Moon and Sun around the Earth—as well as the Earth's rotation with respect to these objects. Such fluctuations are relatively long-period ones compared with the short-period variations which produce magnetic transients.

(1) Atmospheric Tides as the Basis for Geomagnetic Variations

Just as the Moon and Sun produce tides in the oceans of the Earth, tides are created in the Earth's atmosphere as a function of the changing positions and proximities of these bodies with respect to the Earth. Such atmospheric tides, and the influences they exert in expanding or contracting the electrical conducting portions of the ionosphere, make themselves felt through detectable variations in the observed intensity of the external geomagnetic field. These variations comprise periodic functions similar to those produced within the oceanic tides. The Moon's gravitational influence results in a clear-cut semidiurnal effect, as well as a lunar declination effect which is superimposed upon it. A semimonthly lunar variation evident in magnetometer records also corresponds to the semimonthly ocean tidal height variations associated with spring and neap tides. A part of the Sun's gravitational influence in producing atmospheric tides is masked by its expansional heating effects and by the ionization phenomena which its ultraviolet radiation produces.

These several lunar and solar effects on the total external magnetic field of the Earth, and the variations they produce through tidal action, are described in detail below.

(2) The Solar Diurnal and Semidiurnal Variations

During each 24-hour period, various components of the Earth's magnetic field exhibit patterns of magnetic influence associated with the overhead ionospheric currents. However, all magnetic observing stations are not similarly affected—a definite latitude dependence being exhibited. The observed changes in intensity of the terrestrial magnetic field—although not following an identical pattern—ostensibly, through what might be called an "induction process," are related to barometric fluctuations in atmospheric tides. The latter phenomenon involves a small observed rise and fall in atmospheric pressure at the ground surface caused by corresponding adjustments in the pressure of the air in the high atmosphere above the observing station. These particular tidal fluctuations in the upper atmosphere, although produced in their main influence by causes other than gravity, nevertheless act in a manner similar to tides in the ocean waters. Minute but detectable incremental adjustments in sea-level atmospheric pressure are created, on the average, each 24 hours, with secondary maxima and minima at 12-hour intervals in between.

Although the Moon's gravitational influence plays the predominant role in the production of the Earth's oceanic tides, the combination of solar heating and expansion of the atmosphere makes the Sun of greater influence in producing atmospheric tides. Both the 24-hour and 12-hour tidally induced maxima in atmospheric pressure observed are attributable to this solar influence.

A harmonic analysis of barograph data recorded at sea level around the world indicates that, in the 12-hour solar cycle between the primary and secondary tidal maxima, barometric pressures may increase, due to atmospheric tides, as much as 1.3 millibars (0.98 millimeter of mercury) at the Equator. This variation is independent of either the presence or the nature of local topography, but the magnitude of the increase in barometric pressure caused by atmospheric tides decreases directly with increasing latitude. The 24-hour component in barometric pressure, averaging approximately 0.7 millibar (0.52 millimeter of mercury) is considerably more dependent upon altitude and geographic effects.

(3) Corresponding Geomagnetic Variations

(a) Solar Variation

Suggestively similar maxima are locally observed in the intensity of the Earth's magnetic field, although actually no midnight peak and no midday peak are observed at many latitudes. It is theorized that distortions of the ionosphere resulting from these tidal atmospheric pressure changes produce fluctuations both in the electric current flow in the ionosphere and in the associated external magnetic field.

At the Equator, the observed magnetic fluctuations roughly parallel the barometric fluctuations—a common maximum being recorded at about 11 a.m., local time. The disturbing influences on the ionosphere in general tend to follow the Sun, but are affected by latitudinal influences and other causes, including the elasticity of the atmosphere. Thus, especially at high latitudes, the magnetic effects may vary considerably, and either a maximum or a minimum may be observed at 11 a.m.

(b) Lunar Variation

A much smaller, though similar magnetic variation, amounting to less than 1/10th the solar influence, is produced by the tidal action of the Moon upon the upper atmospheric layers, and is observable with the changing phases of the Moon. The corresponding atmospheric tidal influence at the Equator and sea level, in the same terms as the preceding comparisons, results in a fluctuation of about 0.08 millibar (0.06 millimeter of mercury) in barometric pressure at each $12^h25.5^m$ interval (a period equal to one-half that between two successive transits of the Moon across the local meridian of any place, on the average).

As an academic matter, the reinforcing geomagnetic influences of Moon and Sun should be greater in their maximum tide-raising tendency at perigee-syzygy, if these effects are also combined with, rather than negated by, the radiational effects of the Sun.

D. Geomagnetic Illustration of the Increase in Velocity of Tidal Currents at Times of Perigee-Syzygy

A slightly different verification of the increase of gravitational force on the Earth's tidal waters resulting from the alignment of the Moon with the Sun at perigee-syzygy is made possible by the use of geophysical measurements. These involve the fact that the seawater itself (acting as a conductor of electricity) can generate its own electrical current flow when caused to pass through the Earth's lines of geomagnetic force.

The minute electrical potential gradient thus established can be accurately measured between two electrodes floating on the surface of the water and moored to the ocean floor. The small increment in electrical voltage built up as the flow of water between the electrodes increases will be a determinable function of the water velocity. (This same relationship comprises the working principle of the von Arx electromagnetic current meter. See William S. von Arx, *An Introduction to Physical Oceanography*, Reading, Mass., 1962, pp. 260–279.)

In the case of tidal currents, these velocities will, in turn, increase in proportion to the tide and current generating forces of the Moon and Sun—forces significantly amplified at the times of perigee-syzygy.

Since the effect of perigee-syzygy on the Earth's external magnetic field is real but minuscule, the resulting variation in electrical potential (of the magnitude observed) is due to the increase in water velocity subject to the reinforcing gravitational action of the Moon and Sun at syzygy—together with the proximity of the Moon to the Earth at perigee. [The mean epoch of perigee-syzygy is 1918 September 20, 2100^h (G.c.t.), in the actual circumstance illustrated in figure 166, which is redrawn from an article by F. B. Young, H. Gerrard, and W. Jevons, "On Electrical Disturbances Due to Tides and Waves," *Philosophical Magazine and Journal of Science* (London, Edinburgh, and Dublin), vol. XL (6th series, July–December 1920), pp. 149–159, fig. 5.]

The very definite reduction in positive amplitude of successive curve crests from near the time of perigee-syzygy on September 20 (accompanied by perigean spring tides) to lunar quadrature (neap tides) on September 27 is clearly revealed in this diagram. These individual curve crests correspond to the instants of greatest tidal current flow near the times of low water in each successive day. Complementing figure 153b, this diagram provides a realistic illustration of the increase in the velocity of tidal currents—just as the former shows the increase in the rate of tide rise subject to the influence of perigee-syzygy.

SUPPLEMENTARY COMMENTS, SPECIFIC LITERATURE CITATIONS, AND CASE EXAMPLES IN CONNECTION WITH THE INFLUENCES OF PERIGEE-SYZYGY ALIGNMENTS AND PERIGEAN SPRING TIDES

1. Storm Surge Models and Tidal Flooding

In addition to the wide range of papers on storm surges and their damage to the coastline listed in category (18) of the bibliography, numerous specific studies have been conducted and, in some cases, hypothetical models of the associated hydraulic actions have been established, covering various local harbors or estuaries. Illustrative of the reports on such projects are: Robert L. Miller, et al., "Preliminary Study of Tidal Erosion in Great Harbor at Woods Hole, Mass.," U.S. National Technical Information Service, *Government Reports Announcements* (abstract only), *72,* 89 (1972); Harry L. Bixby, Jr., *Storms Causing Harbor and Shoreline Damage Through Winds and Waves Near Monterey, Calif.,* (master's thesis), Naval Postgraduate School, Monterey, Calif. (1962) 186 pp.; B. W. Wilson, et al., *Feasibility Study for a Surge-Action Model of Monterey Harbor, Calif.,* Science Engineering Associates, San Marino, Calif., Contract Report No. 2–136 for U.S. Army Engineer Waterways Experiment Station, Corps of Engineers, Vicksburg, Miss. (1965) 199 pp.; and Abraham S. Kussman, "The Storm Surge Problem in New York City, *Transactions of the New York Academy of Sciences,* series II, vol. 19, No. 8, pp. 751–763 (1957).

2. Engineering Protection Against Storm Surges and Tidal Flooding

Aspects of protection against the ravages of storm surges have been discussed in such articles as: C. A. Evans, et al., "DuPont Tide and Storm Warning Service," American Meteorological Society *Proceedings, 1st National Conference on Applied Meteorology, Hartford, Conn., October 28–29, 1957,* Boston, Mass., pp. A–8 to A–18 (1958); P. C. Hyzer, "Hurricane Tidal Flood Protection, Narragansett Bay Area, Rhode Island and Massachusetts," *Shore and Beach, 3,* 16–19 (1965); George M. Mayfield, "Surveying and Mapping Aspects, Storm Tide Protection," *Surveying and Mapping, 92,* 1–10 (1966); and Basil W. Wilson, "Design Sea and Wind Conditions for Offshore Structures," *Proceedings, Offshore Exploration Conference (OECON)* Long Beach, Calif., 1966, M. J. Richardson, Inc., Palos Verdes Estates, Calif., pp. 665–708 (1966).

3. Possible Coincidence of Tsunamis and Perigean Spring Tides

The especially severe threat to Pacific coastal regions in the possible coincidence of perigean spring tides and earthquake-produced seismic sea waves or tsunamis is included in a report by Charles Petrauskas, et al., in *Frequencies of Crest Heights for Random Combinations of Astronomical Tides and Tsunamis Recorded at Crescent City, Calif.,* University of California, College of Engineering Laboratory, Technical Report No. HEL. 16–18, Berkeley, Calif. (1971) 70 pp. (See also fig. 167, relating to a similar event on the east coast.)

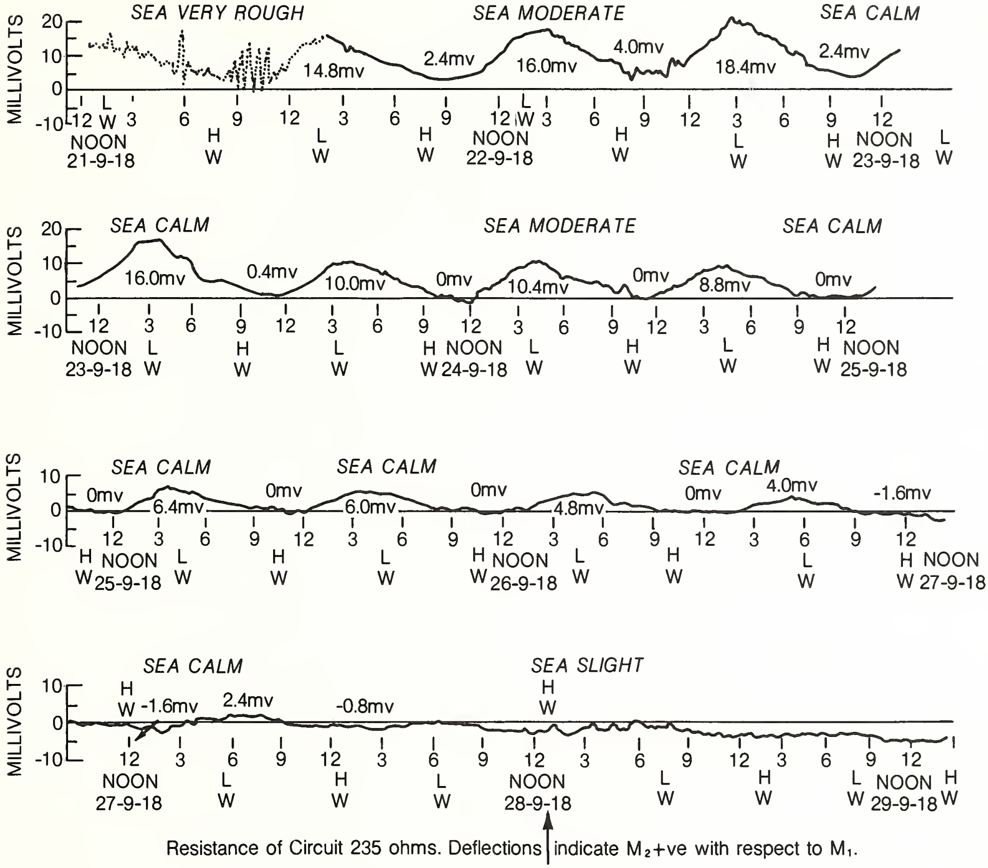
4. Concepts of Earthquake Triggering

A tide-enhancing astronomical alignment of perigee-syzygy, with a separation-interval of only -14^h, occurred at 0000^h (P.s.t.) on November 21, 1976. With a higher high water of 7.1 ft occurring at 0805 on November 21, the resulting maximum daily range of the perigean spring tide predicted for Los Angeles (Outer Harbor) on November 21 was 8.6 ft, or 3.2 ft in excess of the diurnal range (difference in height between mean higher high water and mean lower low water) which is 5.4 ft. at this station.

At 0955 on November 22, an earthquake of magnitude 3.8 on the Richter scale occurred below the sea floor some 24 miles west of Los Angeles, Calif. The epicenter was situated 7 miles south of Malibu, among a maze of offshore faults in Santa Monica Bay which are related to the San Andreas fault.

This was succeeded at 0320 (P.s.t.) on November 26 by another earthquake of magnitude 6.3, with epicenter in the Gorda Basin, north of Ferndale, Calif., at a point near to that at which the principally offshore Mendocino fracture zone intersects the San Andreas fault. Maximum perigean spring tides were predicted for nearby Eureka, Calif., at 1204 (P.s.t.) on November 22, with the maximum daily range of 7.8 ft on November 25 (subject to the continuing influence of the perigee-syzygy alignment) being still 1.1 ft above the [mean] diurnal range of 6.7 ft at this location. The time of higher high water at Eureka on November 25 was predicted for 1429 (P.s.t.). No severe weather systems or

MOORED ELECTRODES M_1 AND M_2 200 YARDS APART



Resistance of Circuit 235 ohms. Deflections indicate M_2+ve with respect to M_1.

FIGURE 166.—(Discussed in text.)

The New York Times
Tues., Nov. 19, 1929
Page 20, Cols. 2, 3

QUAKE FELT HERE; TIDE FLOODS SHORES

Seismograph Needle Breaks at Fordham—Father Lynch Sees Fault in Sea as the Cause.

High Water Sweeps Bridge Away

. . . New York City and vicinity distinctly felt the tremor that followed the earthquake off the coast of Nova Scotia yesterday afternoon. High tides preceded and followed the shock, sending a high surf pounding up the beaches all along the northern shore of Long Island Sound, along the north shore of Queens and on the coast of Northern New Jersey. Queens communities suffered considerable damage as a result of the flood tides.

Father Joseph Lynch, who has charge of the seismograph at Fordham University, said it was quite possible that the extremely high tides and the disturbance in the ocean were related . . .

. . . Father Lynch said that the seismograph at Fordham registered the first shock of the quake at 3:31 P. M. The tremors continued for several hours after that, with particularly severe disturbances recorded at 3:35:7 and 3:37.37. Three minutes later another sharp shock was shown by the needle . . .

Shock Dislodged Needle.

"One of the shocks was so violent that the needle was dislodged from its position," Father Lynch declared. "I do not think this quake was greater than the one that was felt in the New England States and in New York about three years ago."

Checking up with the man in charge of the seismograph at St. Louis University, which is located about 1,712 miles from the supposed centre of the shock, Father Lynch reached the conclusion last night that the disturbance was caused by a fault in the ocean or in the Gulf of St. Lawrence.

"We cannot place the centre definitely until we have taken a more accurate check-up," he declared. "I believe the disturbance today was the end of the fault that occurred in the St. Lawrence Valley, somewhere near the Saguenay River, three years ago, but I cannot say definitely whether it is the end of the fault until we have located the centre within a mile or so."

The authorities in the American Museum of Natural History said they believed the shock was one of the most violent recorded on their seismograph within the past twelve years. According to their figures it began at 3:31 P. M. and lasted one hour. They estimated that the centre of the disturbance was approximately 465 miles from New York, while Father Lynch said he estimated its distance from New York at 880 miles . . .

. . . A sand barge owned by the Hugh McGeeney Company, Inc., of Manhattan was caught by the swift-rising tide and was swept against a bulkhead at the Long Island Railroad drawbridge in Flushing Creek . . .

. . . Gasoline stations along Northern Boulevard, west of the Flushing Bridge, were under several feet of water when the tide was at its maximum height and at Sands Boathouse, near the Flushing Bridge, a flotilla of dories was put into service to remove people from the inundated areas . . .

. . . The Coast Guards at Sandy Hook station said that an unusually heavy tide began running at 8 A. M. and heavy seas came up . . .

. . . They agreed that it was an extremely high tide even for "full moon tide." . . .

ALL WARNED FROM PELEE.

Flares From Martinique Volcano and Rumblings Cause Fear of Eruption.

FORT DE FRANCE, Martinique, Nov. 18 (AP).—The government of Martinique today warned all persons to evacuate the zone at the foot of Mont Pélée owing to the increasing activity of the volcano. For the first time since the activity began flares of light were constantly noticed during the night from Saturday to Sunday. They seemed to come through a split in the upper part of the volcano's cone on the slope toward St. Pierre, which was destroyed with great loss of life in 1902.

The split was almost vertical and about 240 feet high. The flashes of light were acompanied by underground rumblings, which were undoubtedly of volcanic origin . . .

1929 Nov. 17
22h e.s.t. (+54)

54

FIGURE 167.

strong onshore winds prevailed during this period to provide any further tidal amplification.

The November 22 earthquake followed by almost exactly one anomalistic month (27.528^d compared with 27.555^d) the first of a series of 12 minor earthquakes which occurred in north Orange County, Calif. (near Fullerton) beginning at 2115 (P.s.t.) on October 24, and persisting intermittently until early on October 26. The largest was of magnitude 2.0. This series of small earthquakes occurred some 2–3 days after a close perigee-syzygy alignment whose mean epoch was 1976 October 23 0100^h (P.s.t.), $P-S=+8^h$.

A series of some 60 minor earthquakes also had occurred in the area of Brawley, Calif., on November 4 (i.e., within two days of apogee-syzygy, having a mean epoch of 1976 November 6 1100^h P.s.t.). The dual perigee-apogee occurrence of these multiple earthquake events, however meager in terms of the total number and variety of earthquakes, gives interesting grounds for speculation as to the possibility, previously suggested, of a contractional-expansional cycle based upon an increased amplification and reduction of the earth-tide raising forces caused by the near-coincidence of perigee-syzygy and apogee-syzygy, respectively. A similar relationship has been identified in the production of moonquakes at both perigee and apogee. [See G. Latham, et al., *Science, 174,* 687–692 (1971).] Other positive correlations have been detected between such periods of gravitational maxima and both earthquake swarms and aftershocks. [See *Geophysical Research Letters, 2,* 506–509 (1975).]

Conversely, in an article by L. Knopff on "Earth Tides as a Triggering Mechanism for Earthquakes," *Bulletin Seismological Society of America, 54,* 1865 (1964), and another by J. S. Simpson having the same title in *Earth and Planetary Science Letters* (Amsterdam, The Netherlands), *2,* 473 (1976), these authors refute any major triggering of earthquakes by the lunar gravitationl influences producing oceanic and earth tides.

Another conceivable mechanism for earthquake triggering exists in the concept of tidal loading, which itself is a function of enhanced gravitational tide-raising forces. This permits a similar question to be raised: Were all four of the multiple earthquake events above cited, having epicenters offshore or close onshore, but additional earth tremors among the many resulting from California's very active fault zones—or are there contributing ocean tide-loading factors which further enhance the earthquake potential of these and other seismic-prone areas peripheral to the Pacific? (See also the recorded Atlantic coast effects in fig. 168.)

In his paper "Triggering of the Alaskan Earthquake of March 28, 1964, and Major Aftershocks by Low Ocean Tide Loads," *Nature, 210,* 893 (1964), Eduard Berg attributes the triggering action in the case of this 1964 earthquake to tidal loading.

As early as 1929 in a contribution titled "Tilting Motion of the Earth['s] Crust Caused by Tidal Loading," *Bulletin of the Earthquake Research Institute* (Tokyo, Japan), *6,* 85 (1929), R. Takahasi points out that, near the shore, a crustal deformation caused by the tidal load produced by high ocean waters can amount to nearly 50 times the deformations associated with tides in the solid Earth. He cites a specific example where the maximum of such crustal deformations occurred accompanying an *ordinary* spring tide on August 15–17, 1928. However, the possible triggering of earthquakes by such deformations in the crust caused by tidal loading is still a matter of open speculation, together with the question of shear enhancement along fault planes induced by the effects of earth tides.

E. Groten and J. Brennecke in a paper on "Global Interactions Between Earth and Sea Tides," *Journal of Geophysical Research, 78,* 8519–26 (1973) point up the need for further knowledge relating to both the lateral attraction and vertical loading influences upon earth tides caused by unusually high ocean tides.

G. P. Tanrazyan in an article "Tide-Forming Forces and Earthquakes," *Icarus, 7,* 59–65 (1967) substantiates a strong positive correlation between the lunar alignment at perigee-syzygy and earthquakes observed in the U.S.S.R. He also extends an earthquake-tidal force relationship to deep-focus and suboceanic-floor earthquakes in his article "On the Seismic Activity in the Area of the North-western Pacific Ocean Margin," *Akademiya Nauk SSSR, Izvestiya, Seriya Geofizicheskaya* (Moscow, U.S.S.R.) (1958) pp. 664–668.

Numerous papers have been published establishing a relationship between lunar phase relationships, earth tides, and earthquake microseisms. Typical examples are in: *Journal of Geophysical Research, 81,* 2543–55 (1967); *Geophysical Research Letters, 2,* 506–9 (1975); and *Bulletin of the Seismological Society of America, 64,* 2005–6 (1974).

F. W. Klein in a comprehensive article in *Geophysical Journal, Royal Astronomical Society, 45,* 245–295 (1976) tabulates the results of a computerized analysis to show a significant positive correlation between the occurrence of earthquake swarms in the Imperial Valley of California and astronomically induced earth tides. He identifies both ocean loading and shear enhancement as probable triggering mechanisms.

The present state of knowledge in this elusive field of investigation involving the search for a possible correlation between changing distances and aspects of the Moon and earthquakes would, with any degree of consistency, only allow for the following general precepts: (1) the existence of a possible correlation between either of the positions of lunar syzygy and the production of microseisms; (2) the absence, at present, of any definitive correlation between the occurrences of lunar syzygy or perigee-syzygy and seismic events of intermediate to large magnitudes on the Richter scale—although some acceptable correlations have been found with earthquakes of magnitude > 5, occurring at depths < 30 km, with fault motion (slip-dip) at least 30 percent in the vertical [*Geotimes, 19,* 30 (1974)]; (3) among those seismic events in which an acceptable correlation with syzygy or perigee-syzygy has been established, all are of shallow-focus origin, but those in which fault motion (strike-slip) is parallel to the Earth's surface are generally excluded.

5. *Tidal Loading*

The effects of vertical movement of the crust produced by tidal loading are summarized in a report by A. Waalewijn, "Hydrostatic Measurement of Vertical Movement of the Coast Dependent on the Tides," in: *Contributions to IAG Special Study Group 2.22 by the Permanent Service for Mean Sea Level,* J. R. Rossiter, ed., presented at the 1970 Coastal Geodesy Symposium held in Munich, Germany, pp. 239–247 (1970).

6. *Earth Tides*

A significant summary of the varying values of earth tides has been presented in an article by J. T. Kuo, et al., "Transcontinental Tidal Gravity Profile Across the U.S.," *Science, 168,* 968–971 (1970). This survey also reveals the futility of attempting to apply the theoretically derived data of corange and cotidal charts to determine the indirect effects produced by ocean tides upon tides in the solid Earth.

The New York Times
Tues., March 10, 1931
Page 1, Col. 2

Earth Shivers Are Linked To the World-Wide Storms

Special to The New York Times.

CAMBRIDGE, Mass., March 8.—On the heels of the storm and record tide which swept the New England coast Wednesday and Thursday, leaving a trail of damage and ruin in and around Boston, the Harvard seismograph station today came forward with additional documentary evidence of the destructive forces at work coincidental with the flood tide, but defying scientific explanation.

The seismograms of the two days of the storm and yesterday give a record which even a layman can readily distinguish from normal oscillations and from the characteristic records of earthquakes.

Microseisms, as explained by Lewis Don Leet, instructor in seismology, who is in charge of the station, are microscopic shakings or rhythmic motions of the ground which continue for hours and, as in this case, for days. They have puzzled seismologists for many years . . .

1931 Mar. 4
5.5 e.s.t. (0)

D–57

FIGURE 168.

7. Crustal Tilt

The further importance of tidally induced crustal tilt in the case of precise geodetic leveling measurement is obvious. The effects on both gravity measurements and land tilt produced by a large mass of tidal water which piles up in an embayment or landlocked estuary have been well demonstrated in such investigations as "The Response of the Earth to Loading by the Ocean Tides Around Nova Scotia," by A. Lambert, *Geophysical Journal, Royal Astronomical Society, 19,* 449–77 (1970).

8. Deflection of the Vertical

The deflection of the vertical as the result of high ocean tides and its importance to geodesy have been discussed in such articles as that by G. W. Lennon, "The Deviation of the Vertical at Bidston in Response to the Attraction of Ocean Tides," *The Geophysical Journal of the Royal Astronomical Society, 6,* 64–84 (1962).

9. Geomagnetic Effects

Examples of the influence of lunar tides upon geomagnetism and aeronomy are instanced by: E. S. Batten, *Comparison of Tidal Theory with Lower Thermospheric Wind Observations,* Rand Corporation Papers No. P–4655 (May 1971) 16 pp., and *Tidal Winds in the Mesosphere and Ionosphere,* (Ph. D. Thesis), University of California, Los Angeles, Calif. (1970) 137 pp.; P. Amayene, "Simultaneous Neutral Wind and Temperature Oscillations Near Tidal Periods in the *F*-Region Over St. Santin," *Journal of Atmospheric and Terrestrial Physics* (Oxford, England), *35,* 1499–1505 (1973); Jagdish Chandra Gupta, "Special Analysis of Geomagnetic Variations to Study the Tidal and the Storm Modulation Effects," *Planetary and Space Science* (Oxford, England), *20,* 1613–1625 (1972); R. D. Harris and R. Taur, "Influence of the Tidal Wind System in the Frequency of Sporadic *E* Occurrence," *Radio Science,* Washington, D.C., *7,* 405–410 (1972); and Windele, et al., "Sea Tidally Induced Variations of the Earth's Magnetic Field (Leakage of Current from the Atlantic)," *Nature, 230,* 296, 317–318 (1971).

10. Ecological Aspects

Important environmental influences of exceptionally high tides are described in such papers as that by N. M. Ridgeway, "Directions of Drift of Surface Oil with Wind and Tides," *New Zealand Journal of Marine and Freshwater Research, 6,* 178–184 (1972); B. Johns, "Mass Transport in Rotatory Tidal Currents," *Pure and Applied Geophysics, 60,* 107–116 (1965); and J. Sherman Bleakney, "Ecological Implications of Annual Variations in Tidal Extremes, *Ecology, 53,* 933–938 (1972).

11. Internal Waves

Recurrent evidences have shown up in the scientific literature relating the phenomenon of *internal waves* to the syzygy position of the Moon—with the most significant correlation appearing to exist in connection with the extra strong subsurface currents running in narrow straits or channels at times of perigee-syzygy. A typical instance of this relationship was the detection of large-amplitude internal waves in the Great Channel between Great Nicobar Island and Sumatra during the Indian Ocean Expedition of the U.S. Coast and Geodetic Survey ship *Pioneer* in 1964. The internal waves were first discovered on June 12 (G.c.t.), within 2 days of an alignment of perigee-syzygy having a mean epoch of June 10 0300^h (G.c.t.) and a separation between components of -2 hours. The presence of the internal waves was manifest at the sea surface by a phenomenon resembling tide rips. [See bibliography, category (11), Perry, R. B., and Schimke, G. R. (1965).]

In a direct followup to this earlier sighted occurrence, a letter dated March 4, 1977, from the chief scientist of the Exxon Production Research Co., pursuing offshore drillship operations in the Andaman Sea, indicated "with fair assurance that internal wave activity in the Andaman Sea corresponds very well with spring tide activity . . . the maximal internal wave activity occurring within a four-day period centered around the spring tides." Occasional internal wave activity noted during other times of the month "is much reduced from that occurring near the spring tides."

12. Turbidity Currents

The possibility that strong underwater currents produced at the times of perigean spring tides might also be associated with subsurface turbidity currents is raised by the report of a NOAA two-man submarine diving operation at the head of Oceanographer Canyon off the east coast of North America on July 17, 1974. A perigee-syzygy alignment occurred on July 19, 1974, with the mean epoch of perigee-syzygy at 1000^h (e.s.t.). The report reads, in part, as follows.

"Dive #14. Head of Oceanographer Canyon . . . heading 180° . . . 7/17/74 . . . Gamma Dive #441.

0846 . . . on bottom 565′ . . . Savoy silt with a few erratic boulders . . . started down slope between the two major tributaries . . . At 600′ we started picking up a slight westerly current (possibly coming out of the N.E. head) . . . This current became stronger with time and depth . . . Visibility was 30–40′ . . . Temperature 49.5° F. at 600′ . . . Continuing down to 700′ the current became quite strong . . . water temperature at 700′ was 51°! . . . Suddenly we were enveloped in a cloud of sediment . . . Visibility <2′ . . . The sub started moving sideways (to the west) quite rapidly ([velocity] at least 2 knots—hard to estimate, but the bottom was going by very fast . . . observer thought 4 or 5 knots) . . . I got the sub turned around and started upslope (to the north) while still drifting rapidly to the west . . . the bottom here was silty with many pebbles and 3–5″ ripples (orientation unknown) . . . upon reaching the 650′ level we suddenly came into still clear water . . . visibility 30′ . . . no current . . . turning around I could see the turbid area below us. All very strange and exciting . . . the whole thing took only 5 (?) minutes. . . ."

13. Fish Migration

In an earlier technical paper by Otto Pettersson on "The Connection Between Hydrographical and Meteorological Phenomena," *Quarterly Journal of the Royal Meteorologi-*

cal Society, 38, 173–191 (1912), the author discusses certain tidal and tidal-current phenomena in connection with climatology. He relates the undercurrent of the Skagerak and Kattegat to the declination of the Moon and its changing distance from the Earth (thus indicating a deep-water tidal movement of the tropical and parallactic type). These deep-water movements are, in turn, associated with the migration of herring shoals into the Kattegat in winter.

Oscillatory movements occurring in the deep waters produce large, long-period submarine waves of differing densities and possessing a distinct correlation with the phase and position of the Moon. The subsurface waves produced in this phenomenon are termed "the Moon waves of the Gullmar fjord." The peaking of these waves (i.e., attainment of their shallowest depths beneath the sea surface) near the times of syzygy is clearly shown in the article.

14. Biological Rhythms

Technical discussions of many aspects of biological rhythms as they relate to tides are contained in John D. Balmer, et al., *An Introduction to Biological Rhythms,* New York (1976) 392 pp. In this work, the various contributors describe (chapter I) the responses to tidal rhythms by fiddler, penultimate-hour, and green shore crabs, as well as sand hoppers and even unicelled diatoms. They also subsequently evaluate the evidence for external timing of biological clocks, certain geophysically dependent rhythms, and the observed propensities among various life forms toward lunar periodisms.

15. Breakup of River Ice

A classic and interesting example of the effect of perigean spring tides in breaking up river ice is contained in a record of natural events which occurred in the colonial period of America. In an article on "Some Old-Fashioned Winters in Boston," Fitz-Henry Smith, Jr.[d] notes (p. 275) an episode that occurred in the winter of 1766:

"The harbor remained frozen from Sunday, Jan. 5 [N.S.] until the following Saturday [Jan. 11] when an extraordinary thaw and south wind dissipated the ice." He further states that "Tudor [e] commented that it was 'very remarkable for the Harbor to frees [sic] up so strong and be so clear again in 6 Days'."

Table 16 shows that syzygy (new moon) occurred on 1766 January 10 at 2000^h (75° W.-meridian time) and perigee at 1400^h on the same date, giving the mean epoch of perigee-syzygy as 1766 January 10, 1700^h (75° W.-meridian time) preceding by just a day [together with the effects of phase- and parallax-age] that on which the ice breakup occurred. The perigean spring tides and their associated strong currents undoubtedly provided an active contributing cause to dissipation of the ice.

[d] Fitz-Henry Smith, Jr., "Some Old-Fashioned Winters in Boston, with Particular Reference to Times When the Harbor Froze," vol. 65, *Proceedings of the Massachusetts Historical Society,* Boston, 1940.

[e] William Tudor, ed., *Deacon Tudor's Diary,* Boston, 1896.

The Challenge of Geophysical Discovery: An Advocacy of Interdisciplinary Cooperation

It is obvious from the preceding sections and chapters that many complex geophysical and biophysical problems exist that are dependent upon both regular variations and irregular extremes in gravitational force, and which, ultimately, only the application of a multidisciplinary scientific approach can solve.

Such cooperative effort as that which motivated the joint National Academy of Sciences-Government agency-academic institution-private research corporation studies of the Great Alaskan Earthquake of 1964 [and which was set down for the record in the prefaces to the 3-volume ESSA (NOAA) publication series on that earthquake] has been demonstrated as both feasible and productive.

In the predominantly empirical, case-study approach of several chapters of the present volume, the large amount of data tabulated giving special attention to details of time and position has been included with a direct purpose in mind—that of providing a suitable base for coordinated use in other related disciplines of science. This plan of presentation is occasioned by a strong feeling that the innovative approaches resulting from overlap and feedback between various related sciences can best serve to reveal and confirm exact new causal connections not previously known—or at least to crystallize knowledge in many of the propositions and concepts earlier enumerated in theoretical form only.

As has been several times remarked in connection with various suggested relationships throughout the immediately preceding pages, available theories are presented which are often not yet fully supported by substantiating data. Further confirmatory evidence is definitely needed to establish such supposed relationships on a firm basis and, at the same time, to determine and verify the exact method of operation of the forces involved. In direct amplification of the latter statement in terms of the ease of its misinterpretation, this work will be concluded on a purely academic note.

Theories are inventions rather than discoveries. Somewhat anomalously, therefore, from a pure research point of view, they may sometimes serve to limit progress to a certain degree rather than to accelerate it—since, after a theory is created, valuable time is often consumed in striving to make data conform to it as a purely mechanistic artifice, instead of this same time being devoted to investigation of the cause of the impelling action itself.

Thus, as a hypothetical example in the field of gravitation presently under discussion, in the days before Sir Isaac Newton a physical law might conceivably have been deduced to explain how an object gets from a point *A* to a point *B* under free-fall without bothering to explain how the motivating force originated, or even how the moving object got underway. Yet, the newly derived law of motion under free-fall, if self-sufficient, would be fully accepted as describing this motion and its effect in getting an object from point *A* to point *B*. To satisfy the physical cause of this action, the assumption might simply have been made that some arbitrary force of attraction exists between *A* and *B*. This assumption would be deemed adequate to fulfill the immediate need.

But science, fortunately, does not work in this "closed-door" environment, satisfied to ignore the cause of any force or action until the need arises to ascertain the cause. Although over 300 years have elapsed since Newton first propounded his descriptive law of gravitation and numerous generations of scientists have sought, unsuccessfully, physically to define the interacting force, the search still goes on in laboratories and research institutions to find a clue to the exact nature of this force.

Nor is this the only gap in fundamental geophysical knowledge. Examples from other fields are equally familiar. Even assuming the validity of the theories propounded for describing various types of motions, the scientist is still at a loss today in endeavoring to define the basic forces which, as single examples: (1) started electrons revolving around the nuclei of atoms; (2) initiated ring currents in the body of the Earth to produce an electromagnetic field; or (3) caused the Sun to rotate on its axis and the planets to revolve around it.

In the realm of other intangible physical entities, such as electromagnetic radiation, neither can he directly answer the question why rays of certain colors of light travel faster than rays of other colors through a medium of the same optical density, nor why rays of short wavelength carry with them more energy than long waves. As yet unanswered also are the reasons why a moving or rotating electron possesses an electrical field, and why a particle of mass exerts a gravitational force. Confronted by such basic questions as these, the depth of our knowledge and understanding of the forces, fields, and physical phenomena of the universe remains grossly inadequate.

Perhaps one of the great benefits which may come out of interdisciplinary research in the geophysical sciences is a reappraisal of our whole scientific thinking—overcoming any Aristotelian-like, conditioned sense of satisfaction with classic theories. With the continuously growing trend in basic research may come a realization that there may be other new and as yet totally undiscovered laws, principles, or factors of physical causation at work—or fundamental modifications required in our existing scientific laws—even including those of gravitation and geomagnetism.

As an example, with respect to gravitation, there is presently no way of knowing whether the gravitational force field averaged for the entire universe might not actually be effective in permeating and altering the local gravity field of the Earth—assuming that this universal, smoothed force field might be of such a small magnitude that its differential effects could not be detected across the relatively short distance comprising the diameter of the Earth. The extension of the available baseline to outer space through the use of artificial satellites, and the conduct of experiments in deep space to evaluate more precisely the gravitational constant—which provides a common denominator for gravitational action through the known universe—should provide important strides forward in this connection.

Appendix

The Basic Theory of the Tides

Introduction

The word "tides" is a generic term used to define the alternating rise and fall in sea level with respect to the land, produced by the gravitational attraction of the Moon and Sun. To a much smaller extent, tides also occur in large lakes, in the atmosphere, and within the solid crust of the Earth, acted upon by these same gravitational forces of the Moon and Sun. Additional nonastronomical factors such as configuration of the coastline, local depth of the water, ocean-floor topography, and other hydrographic and meteorological influences may play an important role in altering the range, interval between high and low water, and times of arrival of the tides.

The most familiar evidence of the tides along our shores is the observed recurrence of high and low water—usually, but not always, twice daily. The term *tide* correctly refers only to such a relatively short-period, astronomically induced vertical change in the height of the sea surface (exclusive of wind-actuated waves and swell); the expression *tidal current* relates to accompanying periodic horizontal movements of the ocean water, both near the coast and offshore (but as distinct from the continuous, stream-flow type of *ocean current*).

Knowledge of the times, heights, and extent of inflow and outflow of tidal waters is of importance in a wide range of practical applications such as the following: Navigation through intracoastal waterways and within estuaries, bays, and harbors; work on harbor engineering projects, such as the construction of bridges, docks, breakwaters, and deep-water channels; the establishment of standard chart datums for hydrography and for demarcating the seaward extension of shoreline property boundaries; the determination of a base line or "legal coastline" for fixing offshore territorial limits, both on the sea surface and on the submerged lands of the Continental Shelf; provision of information necessary for underwater demolition activities and other military engineering uses; and the furnishing of data indispensable to fishing, boating, surfing, and a considerable variety of related water sports activities.

The Astronomical Tide-Producing Forces: General Considerations

At the surface of the Earth, the Earth's force of gravitational attraction acts in a direction inward toward its center of mass, and thus holds the ocean waters confined to this surface. However, the gravitational forces of Moon and Sun also act externally upon the Earth's ocean waters. These external forces are exerted as tide-producing, or so-called "tractive" forces. Their effects are superimposed upon the Earth's gravitational force and act to draw the ocean waters to positions on the Earth's surface directly beneath these respective celestial bodies (i.e., toward the "sublunar" and "subsolar" points).

High tides are produced in the ocean waters by the "heaping" action resulting from the horizontal flow of water toward two regions on the Earth representing the positions of maximum attraction of the combined lunar and solar gravitational forces. Low tides are created by a compensating maximum withdrawal of water from regions around the Earth midway between these two tidal humps. The alternation of high and low tides is caused by the daily (or diurnal) rotation of the solid body of the Earth with respect to these two tidal humps and two tidal depressions. The changing arrival times of any two successive high or low tides at any one location is the result of numerous factors later to be discussed.

Origin of the Tide-Raising Forces

To all outward appearances, the Moon revolves around the Earth, but in actuality, the Moon and the Earth revolve together around their common center of mass, or gravity. The two astronomical bodies are held together by gravitational attraction, but are simultaneously kept apart by an equal and opposite centrifugal force produced by their individual revolutions around the center-of-mass of the Earth-Moon system. This balance of forces in orbital revolution applies to the centers-of-mass of the individual bodies only. At the Earth's surface, an imbalance between these two forces results in the fact that there exists, on the hemisphere of the Earth turned toward the Moon, a net (or differential) tide-producing force which acts in the direction of the Moon's gravitational attraction, or toward the center of the Moon. On the side of the Earth directly opposite the Moon, the net tide-producing force is in the direction of the greater centrifugal force, or away from the Moon.

Similar differential forces exist as the result of the revolution of the center-of-mass of the Earth around the center-of-mass of the Earth-Sun system.

Detailed Explanation of the Differential Tide-Producing Forces

The tide-raising forces at the Earth's surface thus result from a combination of basic forces: (1) the force of gravitation exerted by the Moon (and Sun) upon the Earth; and (2) centrifugal forces produced by the revolutions of the Earth and Moon (and Earth and Sun) around their common centers-of-gravity (mass). The effects of those forces acting in the Earth-Moon system will here be discussed, with the recognition that a similar force complex exists in the Earth-Sun system.

With respect to this *center-of-mass* of the Earth-Moon system (known as the barycenter) the above two forces always remain in balance (i.e., equal and opposite). In consequence, the Moon revolves in a closed orbit around the Earth, without either escaping from, or falling into the Earth—and the Earth likewise does not collide with the Moon. However, at local points on, above, or within the Earth, these two forces are not in equilibrium, and oceanic, atmospheric, and earth tides are the result.

The center of revolution of this motion of the Earth and Moon around their common center-of-mass lies at a point approximately 1,718 km (1,068 mi) beneath the Earth's surface, on the side toward the Moon, and along a line connecting the individual centers-of-mass of the Earth and Moon. (See G, figure 1.) The center-of-mass of the Earth describes an orbit (E_1, E_2, E_3 . .) around the center-of-mass of the Earth-Moon system (G) just as the center-of-mass of the Moon describes its own monthly orbit (M_1, M_2, M_3 . .) around this same point.

1. The Effect of Centrifugal Force

It is this little-known aspect of the Moon's orbital motion which is responsible for one of the two force components creating the tides. As the Earth and Moon gravitate around this common center-of-mass, the centrifugal force produced is always directed away from the center of revolution in the same manner that an object whirled on a string around one's head exerts a tug upon the restraining hand. All points in or on the surface of the Earth acting as a coherent body acquire this component of centrifugal force, just as all points on an object whirled around the head tend to fly outward under the action of centrifugal force. And, since the center-of-mass of the Earth is always on the opposite side of this common center of revolution from the position of the Moon, the centrifugal force produced at any point in or on the Earth will always be directed away from the Moon. This fact is indicated by the common direction of the arrows (representing the centrifugal force F_c) at points A, C, and B in figure 1, and the thin arrows at these same points in figure 2.

It is important to note that the centrifugal force produced by the daily rotation of the Earth *on its axis* must be completely disregarded in tidal theory. This element plays no part in the establishment of the differential tide-producing forces.

It may be graphically demonstrated that, for such a case of revolution without accompanying rotation as above enumerated, any point on the Earth will describe a circle around the Earth's center-of-mass which will have the same radius as the radius of revolution of the center-of-mass of the Earth around the barycenter. Thus, in figure 1, the magnitude of the centrifugal force produced by the revolution of the Earth and Moon around their common center-of-mass (G) is the same at point A or B or at any other point on or beneath the Earth's surface. Any of these values is also equal to the centrifugal force produced at the Earth's center-of-mass (C) by its revolution around the barycenter. This fact is indicated in figure 2 by the equal lengths of the thin arrows (representing the centrifugal force F_c) at points A, C, and B, respectively.

2. The Effect of Gravitational Force

While the effect of this centrifugal force is constant for all positions on the Earth, the effect of an external gravitational force produced by another astronomical body may be different at different positions on the Earth because the magnitude of the gravitational force exerted varies with the distance of the attracting body. According to Newton's Universal Law of Gravitation, the force value decreases as the second power of the distance from the attracting body. As a special case, the *tide-raising* force varies inversely as the third power of the distance of the center-of-mass of the attracting body from the surface of the Earth. Thus, in the theory of tides, a variable influence is introduced based upon the different distances of various positions on the Earth's surface from the Moon's center-of-mass. The relative gravitational attraction (F_g) exerted by the Moon at various positions on the Earth is indicated

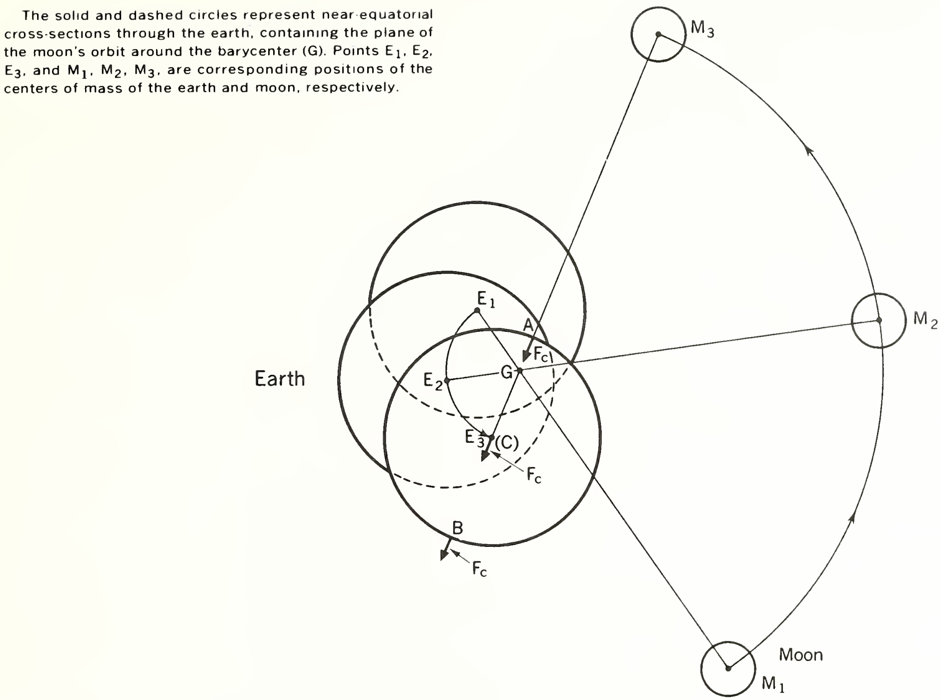


FIGURE 1.—The monthly revolution of the Earth and Moon around the Barycenter of the Earth-Moon System. This revolution is responsible for a centrifugal force component (F_c) necessary to the production of the tides.

in figure 2 by arrows heavier than those representing the centrifugal force components.

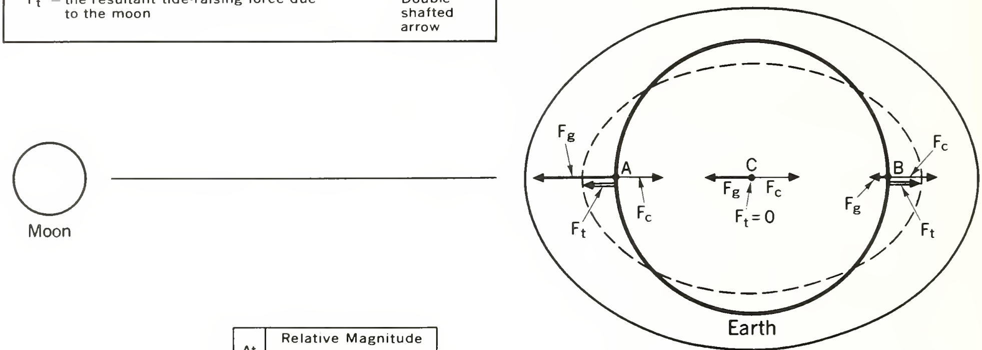
3. The Net or Differential Tide-Raising Forces: Direct and Opposite Tides

It has been emphasized above that the centrifugal force under consideration results from the revolution of the center-of-mass of the Earth around the center-of-mass of the Earth-Moon system, and that this centrifugal force is the same anywhere on the Earth. Since the individual centers-of-mass of the Earth and Moon remain in equilibrium at constant distances from the barycenter, the centrifugal force acting upon the center of the Earth (C) as the result of their common revolutions must be equal and opposite to the gravitational force exerted by the Moon on the center of the Earth. This fact is indicated at point C in figure 2 by the thin and heavy arrows of equal length, pointing in opposite directions. The net result of this circumstance is that the tide-producing force (F_t) at the Earth's center is zero.

At point A in figure 2, approximately 6,378 km (3,963 mi) nearer to the Moon than is point C, the force produced by the Moon's gravitational pull is considerably larger than the gravitational force at C due to the Moon (the Earth's own gravity is, of course, zero at point C). The smaller lunar gravitational force at C just balances the centrifugal force at C. Since the centrifugal force at A is equal to that at C, the greater gravitational force at A must also be larger than the centrifugal force there. The net tide-producing force at A obtained by taking the difference between the gravitational and centrifugal forces is in favor of the gravitational component—or outward toward the Moon. The tide-raising force at point A is indicated in figure 2 by the double-shafted arrow extending vertically from the Earth's surface toward the Moon.

Type of Force	Designation
F_c = centrifugal force due to earth's revolution around the barycenter	Thin arrow
F_g = gravitational force due to the moon	Heavy arrow
F_t = the resultant tide-raising force due to the moon	Double shafted arrow

A north-south cross-section through the earth's center in the plane of the moon's hour angle; the dashed ellipse represents a profile through the spheroid composing the tidal force envelope; the solid ellipse shows the resulting effect on the earth's waters.



At	Relative Magnitude of the Forces Present
A	$F_g > F_c > F_t$
	$\vee \quad \parallel \quad \vee$
C	$F_g = F_c > 0$
	$\vee \quad \parallel \quad \wedge$
B	$F_g < F_c > F_t$

FIGURE 2.—The combination of forces of lunar origin producing the tides. (A similar complex of forces exists in the Earth-Sun system.)

The resulting tide produced on the side of the Earth toward the Moon is known as the *direct tide.*

At point *B,* on the opposite side of the Earth from the Moon and about 6,378 km farther away from the Moon than is point *C,* the Moon's gravitational force is considerably less than at *C.* At point *C,* the centrifugal force is in balance with a gravitational force which is greater than at *B.* The centrifugal force at *B* is the same as that at *C.* Since gravitational force is less at *B* than at *C,* it follows that the centrifugal force exerted at *B* must be greater than the gravitational force exerted by the Moon at *B.* The resultant tide-producing force at this point is, therefore, directed away from the Earth's center and opposite to the position of the Moon. This force is indicated by the double-shafted arrow at point *B.* The tide produced in this location halfway around the Earth from the sublunar point, coincidentally with the direct tide, is known as the *opposite tide.*

4. The Tractive Force

It is significant that the influence of the Moon's gravitational attraction superimposes its effects upon, but does not overcome, the effects of the Earth's own gravity. Earth-gravity, although always present, plays no direct part in the tide-producing action. The tide-raising force exerted at a point on the Earth's surface by the Moon at its average distance from the Earth (384,318 km or 238,855 mi) is only about one 9-millionth part of the force of Earth-gravity exerted toward its center (6,378 km from the surface). The tide-raising force of the Moon, is, therefore, entirely insufficient to "lift" the waters of the Earth physically against this far greater pull of the Earth's gravity. Instead, the tides are produced by that component of the tide-raising force of the Moon which acts to draw the waters of the Earth horizontally over its surface toward the sublunar and antipodal points. Since the horizontal component is not opposed in any way to gravity and can, therefore, act to draw particles of water freely over the Earth's surface, it becomes the effective force in generating tides.

At any point on the Earth's surface, the tidal force produced by the Moon's gravitational attraction may be separated or "resolved" into two components of force—the one in the vertical, or perpendicular to the Earth's surface—the other horizontal or tangent to the Earth's surface. This second component, known as the tractive ("drawing") component of force is the actual mechanism for producing tides. The force is zero at points on the Earth's surface directly beneath and on the opposite side of the Earth from the Moon (since, in these positions, the lunar gravitational force is exerted in the vertical—i.e., opposed to, and in the direction of Earth-gravity, respectively). Any water accumulated in these locations by tractive flow from other points on the Earth's surface tends to remain in a stable configuration, or tidal "bulge."

Thus, there exists an active tendency for water to be drawn from other points on the Earth's surface toward the sublunar point (*A*, in fig. 2) and its antipodal point (*B*, in fig. 2) and to be heaped at these points in two tidal bulges. Within a band around the Earth at all points 90° from the sublunar point, the horizontal or tractive force of the Moon's gravitation is also zero, since the entire tide-producing force is directed vertically inward. There is, therefore, a tendency for the formation of a stable depression here. The words "tend to" and "tendency for" employed in several usages above in connection with tide-producing forces are deliberately chosen since, as will be seen below, the actual representation of the tidal forces at work is that of an idealized "force envelope" within which the rise and fall of the tides are influenced by many factors.

5. The Tidal Force Envelope

If the ocean waters were completely to respond to the directions and magnitudes of these tractive forces at various points on the surface of the Earth, a mathematical figure would be formed having the shape of an oblate spheroid. The longest (major) axis of the spheroid extends toward and directly away from the Moon, and the shorter (minor) axes are centered, and mutually orthogonal to, the major axis. The two tidal humps and two tidal depressions are represented in this force envelope by the directions of the major axis and rotated minor axis of the spheroid, respectively. From a purely theoretical point of view, the daily rotation of the solid Earth with respect to these two tidal humps and two depressions may be conceived to be the cause of the tides.

As the Earth rotates once in each 24 hours, one would ideally expect to find a high tide followed by a low tide at the same place 6 hours later; then a second high tide after 12 hours, a second low tide 18 hours later, and finally a return to high water at the expiration of 24 hours. Such would nearly be the case if a smooth, continent-free Earth were covered to a uniform depth with water, if the tidal force envelope of the Moon alone were being considered, if the positions of the Moon and Sun were fixed and invariable in distance and relative orientation with respect to the Earth, and if there were no other accelerating or retarding influences affecting the motions of the waters of the Earth. Such, in actuality, is far from the situation which exists.

First, the tidal force envelope produced by the Moon's gravitational attraction is accompanied by a tidal force envelope of considerably smaller amplitude produced by the Sun. The tidal force exerted by the Sun is a composite of the Sun's gravitational attraction and a centrifugal force component created by the revolution of the Earth's center-of-mass around the center-of-mass of the Earth-Sun system, in an exactly analogous manner to the Earth-Moon relationship. The position of this force envelope shifts with the relative orbital position of the Earth in respect to the Sun. Because of the great difference between the average distances of the Moon (384,400 km or 239,000 mi) and Sun (149,500,000 km or 92,900,000 mi) from the Earth, the tide-raising force of the Moon is approximately 2¼ times that of the Sun.

Second, there exists a wide range of astronomical variables in the production of the tides caused by the changing distances of the Moon from the Earth, the Earth from the Sun, the angle which the Moon in its orbit makes with the Earth's Equator, the superposition of the Sun's tidal envelope of forces upon that caused by the Moon, the variable phase relationships of the Moon, etc. Some of the principal types of tides resulting from these purely astronomical influences are described below.

Variations in the Range of the Tides: Tidal Inequalities

As will be shown in figure 6, the difference in height, in meters or feet, between consecutive high and low tides occurring at a given place is known as the *range*. The range of tides at any one location is subject to many variable factors. Those influences of astronomical origin will first be described.

1. Lunar Phase Effects: Spring and Neap Tides

It has been noted above that the gravitational forces of both the Moon and Sun act upon the waters of the Earth. It is also obvious that, because of the Moon's changing position with respect to the Earth and Sun (figure 3) during its monthly cycle of phases (29.53 days), the gravitational attraction of Moon and Sun may variously act along a common line or at changing angles relative to each other.

When the Moon is at new phase and full phase (both positions being called *syzygy*) the gravitational attractions of Moon and Sun act to reinforce each other. Since the

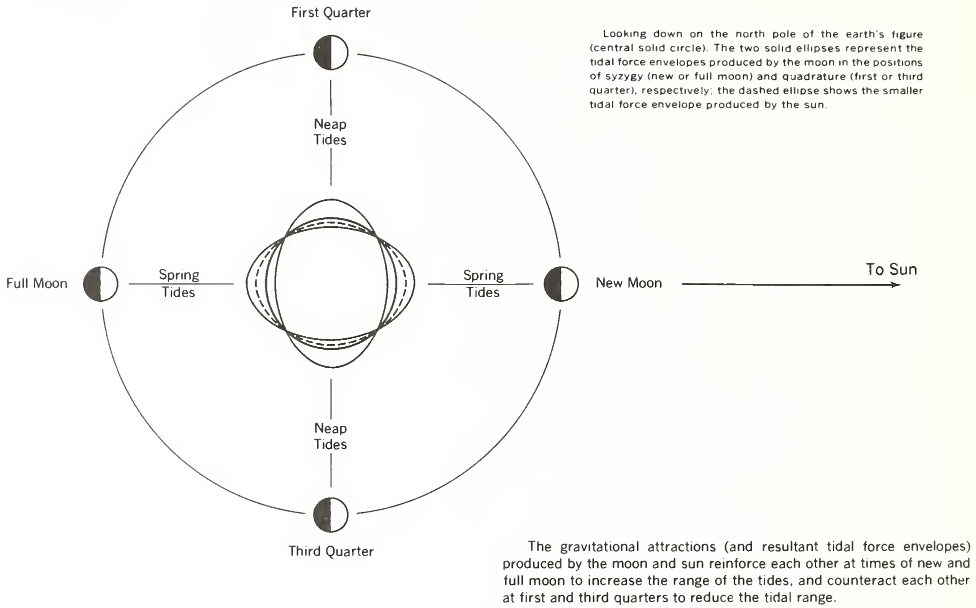


FIGURE 3.—The phase inequality; spring and neap tides.

resultant or combined tidal force is also increased, the observed high tides are higher and low tides are lower than average. This means that the tidal range is greater at all locations which display a consecutive high and low water. Such greater-than-average tides resulting at the syzygy positions of the Moon are known as *spring tides*—a term which merely implies a "welling up" of the water and bears no relationship to the season of the year.

At first- and third-quarter phases (quadratures) of the Moon, the gravitational attractions of the Moon and Sun upon the waters of the Earth are exerted at right angles to each other. Each force tends in part to counteract the other. In the tidal force envelope representing these combined forces, both the maximum and minimum force values are reduced. High tides are lower and low tides are higher than average. Such tides of diminished range are called *neap tides,* from a Greek word meaning "scanty."

2. Parallax Effects (Moon and Sun)

Since the Moon follows an elliptical path (figure 4), the distance between the Earth and Moon will vary throughout the month by about 49,900 km (31,000 mi). The Moon's gravitational attraction for the Earth's water will change in inverse proportion to the third power of the distance between Earth and Moon, in accordance with the previously mentioned extension of Newton's Law of Gravitation. Once each month, when the Moon is closest to the Earth (perigee), the tide-generating forces will be higher than usual, thus producing above-average ranges in the tides. Approximately 2 weeks later, when the Moon (at apogee) is farthest from the Earth, the lunar tide-raising force will be smaller, and the tidal ranges will be less than average. Similarly, in the Sun-Earth system, when the Earth is closest to the Sun (perihelion), about January 2 of each year, the tidal ranges will be enhanced, and when the Earth is farthest from the Sun (aphelion), around July 2, the tidal ranges will be reduced.

When perigee, perihelion, and either the new or full moon occur at approximately the same time, considerably increased tidal ranges result. When apogee, aphelion, and the first- or third-quarter moon coincide at approximately the same time, considerably reduced tidal ranges will normally occur.

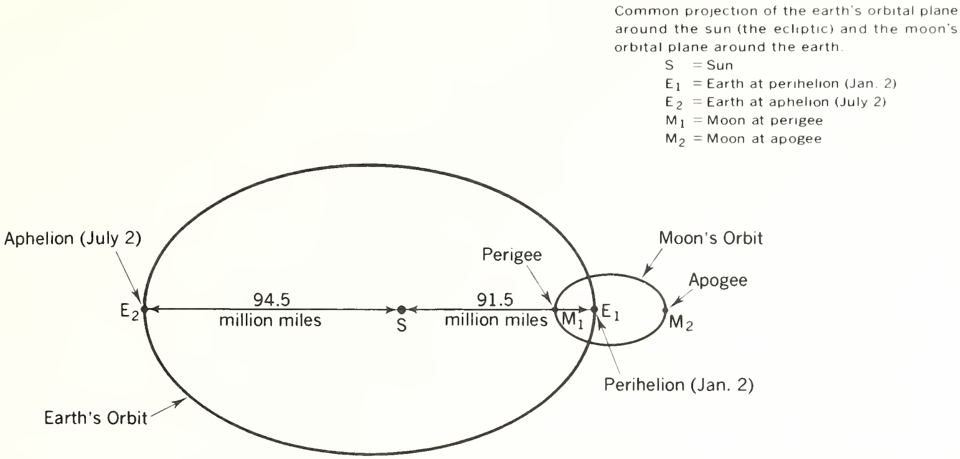


FIGURE 4.—The lunar parallax and solar parallax inequalities. Both the Moon and the Earth revolve in elliptical orbits and the distances from their centers of attraction vary. Increased gravitational influences and tide-raising forces are produced when the Moon is at a position of perigee, its closest approach to the Earth (once each month) or the Earth is at its perihelion, its closest approach to the Sun (once each year). This diagram also shows the possible coincidence of perigee with perihelion to produce tides of augmented range.

3. Lunar Declination Effects: The Diurnal Inequality

The plane of the Moon's orbit is inclined only about 5° to the plane of the Earth's orbit (the ecliptic) and thus the Moon in its monthly revolution around the Earth remains within 28.5° of the Earth's Equator, north and south of which the Sun moves once each half year to produce the seasons. In a similar fashion, the Moon in making a revolution around the Earth once each month, passes from a position of maximum angular distance north of the Equator to a position of maximum angular distance south of the Equator during each half month. (Angular distance perpendicularly north or south of the celestial equator is termed *declination.*) Twice each month, the Moon crosses the Equator. In figure 5, this situation is shown by the dashed outline of the Moon. The corresponding tidal force envelope due to the Moon is depicted, in profile, by the dashed ellipse.

Since the points A and A' lie along the major axis of this ellipse, the height of the high tide represented at A is the same as that which occurs as this point rotates to position A' some 12 hours later. When the Moon is over the Equator—or at certain other force-equalizing declinations—the two high tides and two low tides on a given day are similar in height at any location. Successive high tides and low tides are then also nearly equally spaced in time, and occur uniformly twice daily. (See top diagram in fig. 6.) This is known as the *semidiurnal* type of tides.

Factors Influencing the Local Heights and Times of Arrival of the Tides

It is noteworthy in figure 6 that any one cycle of the tides is characterized by a definite time regularity as well as the recurrence of the cyclical pattern. However, continuing observations at coastal stations will reveal—in addition to the previously explained variations in the heights of successive tides of the same phase—noticeable differences in their successive times of occurrence. The aspects of regularity in the tidal curves are introduced by the harmonic motions of the Earth and Moon. The variations noted both in the observed heights of the tides and in their times of occurrence are the result of many factors, some of which have been discussed in the preceding section. Other influences will now be considered.

The Earth rotates on its axis (from one meridian transit of the "mean sun" until the next) in 24 hours. But as the Earth rotates beneath the envelope of tidal forces produced by the Moon, another astronomical factor causes the time between two successive upper transits of the Moon across the local meridian of the place (a period

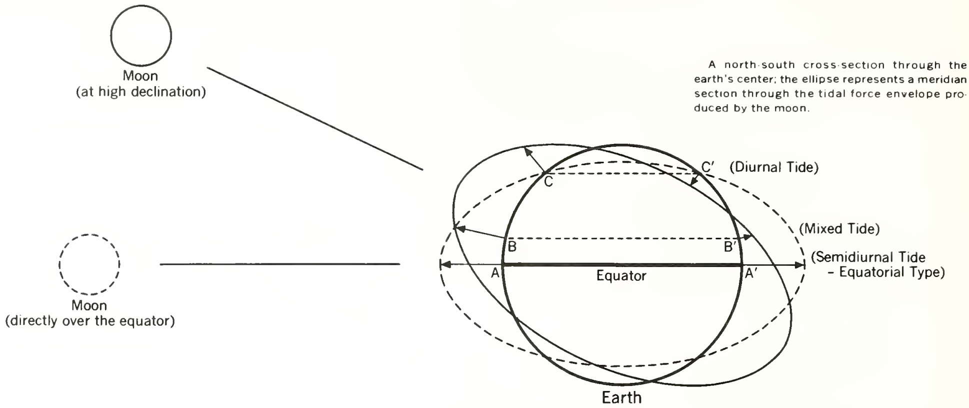


FIGURE 5.—The Moon's declination effect (change in angle with respect to the Equator) and the diurnal inequality. The effects of the diurnal inequality in introducing semidiurnal, mixed, and diurnal harmonic constituents in the tides are also shown. (Compare with fig. 6.)

known as the lunar or "tidal" day) to exceed the 24 hours of the Earth's rotation period—the mean solar day.

The Moon revolves in its orbit around the Earth with an angular velocity of approximately 12.2° per day, in the same direction in which the Earth is rotating on its axis with an angular velocity of 360° per day. In each day, therefore, a point on the rotating Earth must complete a rotation of 360° plus 12.2°, or 372.2°, in order to "catch up" with the Moon. Since 15° is equal to one hour of time, this extra amount of rotation equal to 12.2° each day would require an extra period of time equal to $12.2°/15° \times 60^{m/h}$, or 48.8 minutes—if the Moon revolved in a circular orbit, and its speed of revolution did not vary. *On the average* it requires about 50.415 minutes additional each day for a sublunar point on the rotating Earth to regain this position directly along the major axis of the Moon's tidal force envelope, where the tide-raising influence is a maximum. In consequence, the recurrence of a tide of the same phase and similar height (see middle diagram of figure 6) would take place at an interval of 24 hours 50 minutes after the preceding occurrence, if this single astronomical factor known as *lunar retardation* were considered. This average period of 24 hours 50 minutes has been established as the *tidal day,* but its wide variations form an important aspect of the present monograph.

A second astronomical factor influencing the time of arrival of tides of a given phase at any location results from the interaction between the tidal force envelopes of the Moon and Sun. Between new moon and first-quarter phase, and between full moon and third-quarter phase, this phenomenon can cause a displacement of force components and acceleration in tidal arrival times (known as *priming of the tides*) resulting in the occurrence of high tides before the Moon itself reaches the local meridian of the place. Between first-quarter phase and full moon, and between third-quarter phase and new moon, an opposite displacement of force components and a delaying action (known as *lagging of the tides*) can occur, as the result of which the arrival of high tides may take place several hours after the Moon has reached the meridian.

These are the two principal astronomical causes for variation in the times of arrival of the tides. In addition to these astronomically induced variations, the tides are subject to other accelerating and retarding influences of hydraulic, hydrodynamic, hydrographic, and topographic origin—and may further be modified by meteorological conditions.

The first factor of consequence in this regard arises from the fact that the crests and troughs of the large-scale, gravity-type, traveling wave formations comprising the tides strive to sweep continuously around the Earth, following the position of the Moon (and Sun).

In the open ocean, the actual *rise* (see middle diagram, figure 6) of the tidally induced wave crest is only one to a few feet. It is only when the tidal crests and troughs move into shallow water, against land masses, and into confining channels, that noticeable variations in the height of the water level can be detected.

Possessing the physical properties of a fluid, the ocean waters follow all of the hydraulic laws of fluids. This means that since the ocean waters possess inertia and a

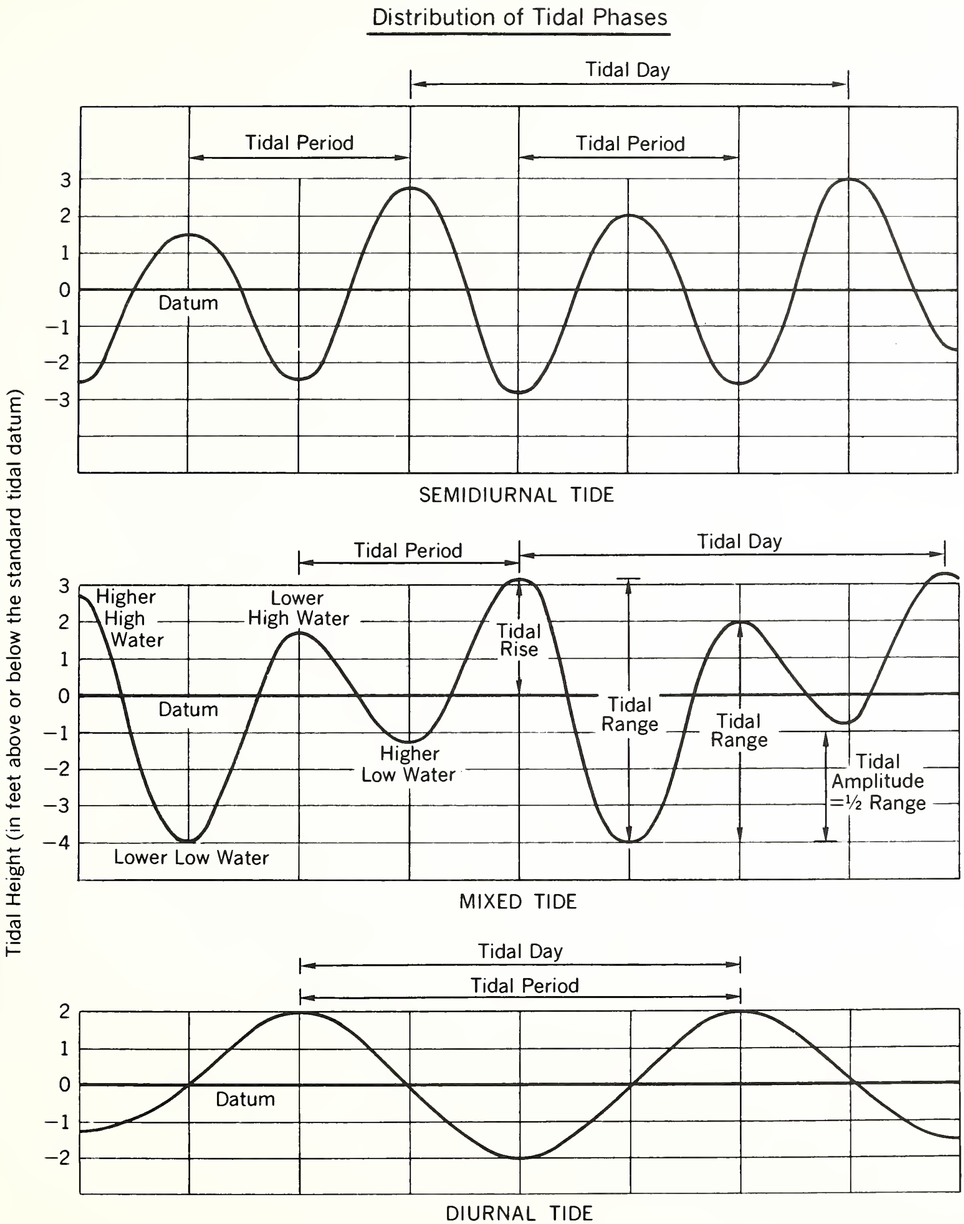


FIGURE 6.—The Principal types of tides.

definite, small internal viscosity, both properties prevent their absolutely free flow, and somewhat retard the overall movement of the tides.

Secondly, the ocean waters follow the principles of traveling waves in a fluid. As the depth of the water shallows, the speed of forward movement of a traveling wave is retarded, as deduced from dynamic considerations. In shoaling situations, therefore, the advance of tidal waters is slowed.

Thirdly, a certain relatively small amount of friction exists between the water and the ocean floor over which it moves—again slightly slowing the movement of the tides, particularly as they move inshore. Further internal friction (or viscosity) exists between tidally induced currents and contiguous currents in the ocean—especially where they are flowing in opposite directions.

The presence of land masses imposes a barrier to progress of the tidal waters. Where continents interpose, tidal movements are confined to separate, nearly closed oceanic basins and the sweep of the tides around the world is not continuous.

Topography on the ocean floor can also provide a restraint to the forward movement of tidal waters—or may create sources of local-basin response to the tides. Restrictions to the advance of tidal waters imposed both by shoaling depths and the sidewalls of the channel as these waters enter confined bays, estuaries, and harbors can further considerably alter the speed of their onshore passage.

In such partially confined bodies of water, so-called "resonance effects" between the free-period of oscillation of the traveling, tidally induced wave and that of the confining basin may cause a surging rise of the water in a phenomenon basically similar to the action of water caused to "slosh" over the sides of a washbasin by repeatedly tilting the basin and matching the wave crests reflected from opposite sides of the basin.

All of the above, and other less important influences, can combine to create a considerable variety in the observed range and phase sequence of the tides—as well as variations in the times of their arrival at any location.

Of a more local and sporadic nature, important meteorological contributions to the tides known as "storm surges," caused by a continuous strong flow of winds either onshore or offshore, may superimpose their effects upon those of tidal action to cause either heightened or diminished tides, or active coastal flooding. High pressure atmospheric systems may also depress the tides, and deep low pressure systems may cause them to increase in height.

Prediction of the Tides

In the preceding discussions of the tide-generating forces, the theoretical equilibrium tide produced, and factors causing variations, it has been emphasized that the tides actually observed differ appreciably from the idealized, equilibrium tide. Nevertheless, because the tides are produced essentially by astronomical forces of harmonic nature, a definite relationship exists between the tide-generating forces and the observed tides, and a factor of predictability is possible.

Because of the numerous uncertain and, in some cases, completely unknown factors of local control mentioned above, it is not feasible to predict tides purely from a knowledge of the positions and movements of the Moon and Sun obtained from astronomical tables. A partially empirical approach based upon actual observations of tides in many areas over an extended period of time is necessary. To achieve maximum accuracy in predictions, a series of tidal observations at any one location ranging over at least a full 18.6-year tidal cycle is required. Within this period, all significant astronomical modifications of tides will occur.

Responsibility for computing and tabulating—for any day in the year—the times, heights, and ranges of the tides—as well as the movement of tidal currents in various parts of the world is vested in appropriate governmental agencies which devote both theoretical and practical effort to this task. The resulting predictions are based in large part upon actual observations of tidal heights made throughout a network of selected observing stations.

The National Ocean Survey, a component of the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce, maintains for this purpose a continuous control network of approximately 140 tide gages at fixed stations as illustrated in figure 7. These are located along the coasts and within the major embayments of the United States, its possessions, and United Nations Trust Territories under its jurisdiction. Temporary secondary stations are also occupied in order to increase the effective coverage of the control network. Tital data are recorded on chart rolls (figure 8), on punched tape (figure 9), and are translated onto punched cards or magnetic tape (figure 10) for electronic computer processing, tabular printout, and analysis.

Predictions of the times and heights of high and low water are published by the National Ocean Survey for a large number of stations in the United States and its possessions as well as in foreign countries and United Nations Trust Territories. These predictions are published each year (approximately 6 months or more in advance) in four volumes. The titles are: *Tide Tables—High and Low Water Predictions* (1) East Coast of North and South America, Including Greenland; (2) Europe and West Coast of Africa, Including the Mediterranean Sea; (3) West Coast of North and South America, Including the Hawaiian Islands; and (4) Central and Western Pacific Ocean, and Indian Ocean.

Predictions of tidal currents are published annually in two volumes, titled: *Tidal Current Tables* (1) Atlantic Coast of North America; and (2) Pacific Coast of North America and Asia.

Although for many years tidal data were calculated by the use of a special harmonic-constant tide-predicting machine developed within the National Ocean Survey, the daily predictions published in these tide tables and tidal current tables are now handled through high-speed automatic data-processing equipment, especially programmed to handle the mathematical evaluation of tidal information.

FIGURE 7.—The NOS tide station on Padre Island, near Port Isabel, Tex.

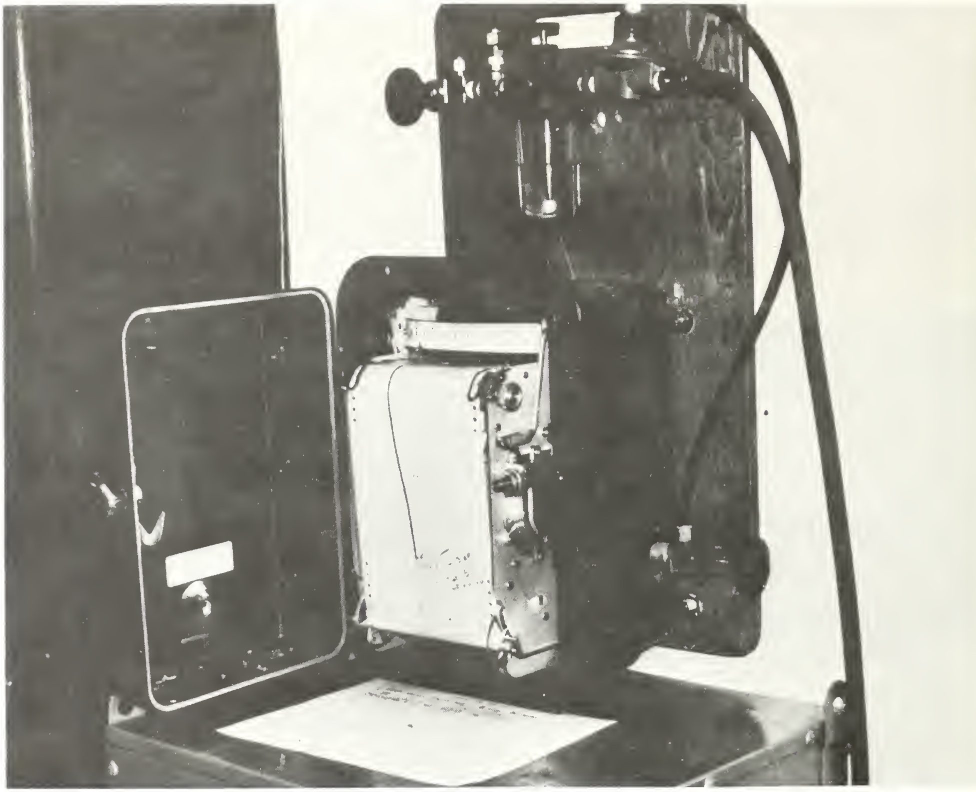


FIGURE 8.—A pressure-recording tide-gage system consisting of: (A) a gas bubbler (background) which senses the tide level by variation of hydrostatic pressure with changing height of the water above the remote, submerged orifice of the tide gage, and (B) a chart recorder or marigraph (center) which traces the water height against time. The resulting marigram trace is run through a marigram scanner, which yields a printout tabulation of hourly tidal heights.

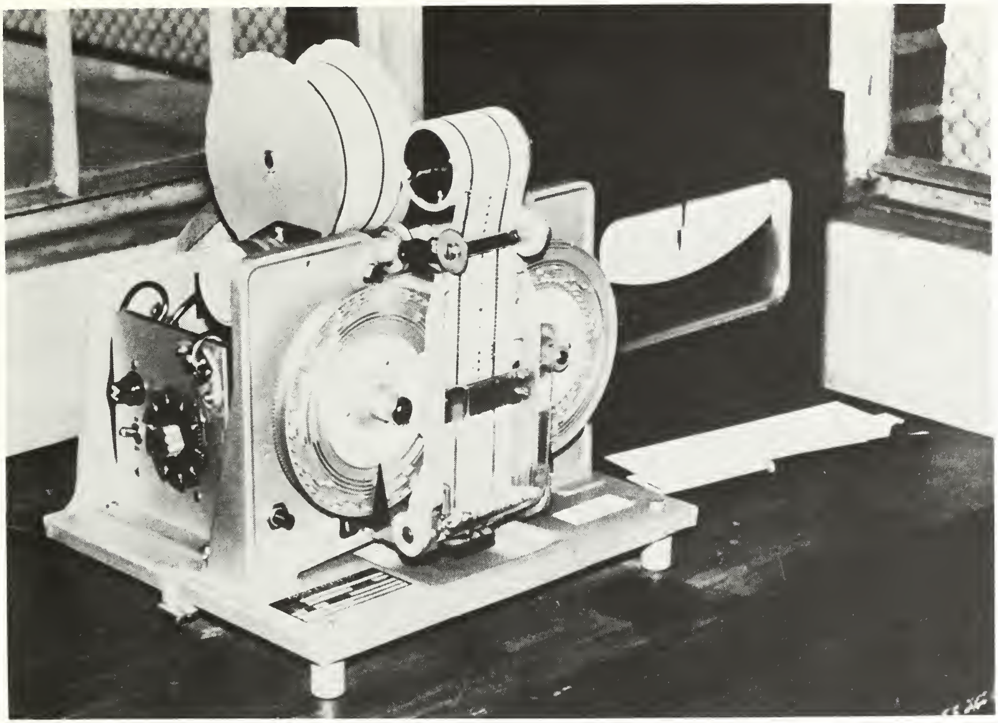


FIGURE 9.—Tidal heights sensed by the float in a tide well are punched on a paper tape in a standard digital (binary-coded decimal) form by the instrument in the center foreground.

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FIGURE 10.—By means of the converter unit (center) the tidal data already punched on tape (right) are transferred onto punched cards (left) which are then fed into an electronic computer for printout, tabulation, and subsequent analysis.

Reference Sources and Notes

Part I

CHAPTER 1

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7. *Boston News-Letter* (New England weekly) of February 21–28, 1723 (O.S.), p. 2, col. 2. [See also under this date in table 5.]
8. *The Boston Gazette and Country Journal* of December 11, 1786 (N.S.), No. 1690, p. 3, col. 1. [See also under this date in table 5.]
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   David M. Ludlum, *Early American Winters 1, 1604–1820*, Boston, Mass., 1966, pp. 70–1.
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   [Map opposite p. 503: a reduced heliotype copy of a tracing of Capt. Parker's Chart of Saybrook Barr, prepared by Charles Burdette, 1885. The original map is in the possession of the Connecticut Historical Society.]
5. Lawrence J. Wroth, *Abel Buell of Connecticut*, Middletown, Conn., 1958, p. 62.
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7. Refer to the first paragraph of the resolution ordered by the Governor and Council of Safety of the State of Connecticut in response to an authorization by the Congress of the United States, as quoted in the present text (reference No. 16).
8. Compare the activities of John Deshon (member of the Eastern Navy Board) in this regard, as quoted from the *Colonial Records of Connecticut* in the present text (reference No. 14); see also the extract from a letter written by William Vernon, a member of the same Navy Board, on March 25, 1778, quoted in Gardner W. Allen, *A Naval History of the American Revolution* (reprint of 1913 ed.) 2 vols., New York, 1962, vol. I, p. 307.

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   William Bell Clark, ed., *Naval Documents of the American Revolution*, Washington, D.C., vol. 2, 1966, p. 498.
10. Entry for the date August 11, 1779, in the diary of Samuel Tully of Saybrook Point, Conn., excerpted in *History of Middlesex County, Connecticut, with Biographical Sketches of Its Prominent Men*, New York, 1884, p. 468.
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11. Letter to the author from Thomas A. Stevens, historian of the Connecticut River, dated January 30, 1975.
    [The following information was added in press, with the issuance of volume 7 of *Naval Documents of the American Revolution*. William James Morgan, editor, Naval History Division, Department of the Navy, Washington, D.C., 1976.]
    Precise contemporary documentation of the Revolutionary War period newly available in this volume confirms several stated opinions with regard to: (1) the date of the *Trumbull's* passage down the Connecticut River; (2) the necessity of an extraordinarily high tide to permit the *Trumbull* to clear the rivermouth bar; and (3) other tactical circumstances associated with the British attack on the Colonies which could well have prevented the *Trumbull's* use of intervening perigean spring tides between November 1776 and August 1779 to good advantage.
    John Cotton, shipbuilder of the *Trumbull* (launched near Middletown, Conn.) wrote to Barnabas Deane, the Continental Navy's designated authority for supervision of ship construction (himself resident at Wethersfield, Conn.) under the date November 18, 1776. In this letter, the former asks for disposition of shipbuilding stores not used, and concludes with a statement of the ship's imminent readiness to make the trip down the Connecticut River:

"Sir/ Middletown Novbr 18th 1776—

When Capn. [Dudley] Saltonstall went away to Wethersfield I had forgott that you had pork Stored with Tewels Butt Desired him to a Quaint you that that pork left with Cooper was taken away, I shall take outt of Tewels Store two Barrels and putt on Board the Ship—

I would be Glad if you Could hire and Send Down a Vessell to Take our Matters from the Ship yd Before we Go a way with the Ship as I Dont Like to Leave them there for fear of a Loss in Some Things that is Much Wanted Especialy Pitch—Nothing further, the Ship Will be Ready to Goe Down Tomorrow Or Next Day Yr[&c.]

John Cotton."

[Morgan, op. cit., p. 197]

In a footnote to a second communication sent on the following day, Cotton notes that the ship has not left yet, and indicates a dependence on high tides in the tidewater river. [Full moon and spring tides would have occurred around the date November 23, which is within the proposed week for "going down" to which Cotton refers. A close perigee-syzygy alignment ($P-S = -5^h$) already had occurred on September 27, 1776, with a mean epoch of 8:30 a.m., 75°W.-meridian time.]

"Sir/ Middletown Novbr 19th 1776

I Wrote to Aquaint you that I have Taken to blls of Your Pork for the Ship Which was in Tewels Store Capn [Dudley] Saltonstall Desires that I would have You Send Down Some Coffee and Sugar and Chocolate if you have Any for the Ships Stores Round to New london What Other he wants I shall Endeavor to Gett here, and the above if they are to be Gott here if they Are they [are] Extravagant the prices Being high, as people are So Exceeding high in their prices they Know well Nott to ask if you have any Spare Bags I Could wish you Would Send Down ½ Dozen as the Ship Wants them and the Capn Mentioned itt To Me I am Sir With Regards [&c.]

John Cotton"

N B The Ship Must Goe away this Week if the Tides Rises

yrs J-C."

[Morgan, op. cit., p. 209]

In a letter from Barnabas Deane to John Hancock datelined "Wethersfield 25th Jany 1777" Deane wrote to the chairman of the Continental Marine Committee as follows:

"Sir

The *Trumbull* Frigate under my Direction Proceeded down Connecticut River the Last of Novr and when She had got within a few miles of the Rivers mouth Two of the Enemys Frigates Appear'd of[f] the River & kept that Station untill the River Froze, I Advisd with Govr Trumbull & his Opinion was to Lay the Frigate up in Some Safe Creek which I did about Twenty miles from the Rivers mouth—Capt Manly Call'd on me with a Letter from Govr Trumbull (a Copy of which you have on the Other Side) And Agreeable to his Advice I have Supply'd Capt Manly with the *Trumbulls* Cannon which I hope will be Agreeable to the Honble Congress; Govr Trumbull has Engaged that the First Cannon made After the Furnace in this State begins Again to Cast Shall be for to Replace those Supply'd Capt Manly with

I am Respectfully [&c.]

Bar[s] Deane"

[Morgan, op. cit., p. 1036]

It is significant in terms of the draft of the *Trumbull* at the time she cleared Saybrook Bar that the ship's cannon were still lacking on September 7, 1779, a month after the vessel left the river mouth. [Cf., Charles O. Paullin, ed. *Out-Letters to the Continental Marine Committee and Board of Admiralty*, August 1776–September 1780, New York, 1924, vol. 2, pp. 106–115.] The *Trumbull* therefore was not encumbered with this extra load of armament on crossing the bar.

A further meaningful letter was transmitted from Nathaniel Shaw, Jr., Continental agent at New London, Conn., to Robert Morris, Chairman of the Secret Committee of the Continental Congress in Philadelphia, datelined "New London Feb 4 1777." This contains the following confirmatory information regarding the situation of unusually high tide required to permit clearance of Saybrook Bar by the frigate *Trumbull:*

". . . I have and shall Continue to supply Capt [Dudley] Saltonstall with what money he may want to get his ship out, at present she is in Connecticut River and am fearful we shall meet with Difficulty in getting her out as she draws so much water, it must be a very extraordinary tide to get her over the Barr, and in case she lies any time on the barr, as the British Ships are Continually passing they may take that opportunity to Destroy her, however you may depend that the greatest prudence will be observed—the Sale of the prize Ship *Clarendon* taken by the *Cabot* is not compleated soon as it can be effected shall send the Accot . . ."

[Morgan, op. cit., p. 1103]

12. Henry P. Johnson, ed., *The Record of Connecticut Men in the Military and Naval Service During the War of the Revolution, 1775–1783*, Hartford, Conn., 1889, pp. 598–9.
13. Charles Oscar Paullin, *The Navy of the American Revolution*, Cleveland, Ohio, 1906, p. 526.
14. Charles J. Hoadly, ed., *The Public Records of the State of Connecticut*, vol. I, October 1776 to February 1778, Hartford, Conn., 1894, p. 113.
15. Ibid., pp. 517–18.
16. Ibid., pp. 567–8.
17. Ibid., p. 569.
18. Charles J. Hoadly, op. cit., vol. II, May 1778 to April 1780, Hartford, Conn., 1895, p. 499.
19. William James Morgan, ed., op. cit., vol. 6, 1972, pp. 322, 350, 360, 706, 759, 763, 892, 949, 1178, 1218-19, and especially p. 1220.
20. Ibid., p. 323.
    History of Middlesex County, Conn., loc. cit.
21. Samuel Adams Drake, *Nooks and Corners of the New England Coast*, New York, 1875, pp. 447–8.
22. Gardner W. Allen, op. cit., vol. II, p. 498.
23. Henry Steele Commager and Richard B. Morris, eds., *The Spirit of 'Seventy-Six*—The Story of the American Revolution as Told by Participants, New York, 1967, p. 956.
24. Charles J. Hoadly, op. cit., vol. XV, p. 206.
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26. John Hamilton Moore, *The New Practical Navigator*, Being an Epitome of Navigation . . ., 12th ed., London, 1796, p. 133.
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35. Ibid., pp. 274–5.
36. Verified by Ships' Histories Branch, Naval History Division, U.S. Navy Department, Washington, D.C.
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38. Annual *Report of the Superintendent of the Coast Survey for 1847*, Washington, D.C., 1847, p. 37; also Appendix No. 13, p. 77.
39. Ibid., in Appendix No. 13, pp. 76–7.
40. Ben Dixon McNeill, *The Hatterasman*, Winston-Salem, N.C., 1958, pp. 138, 282.
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43. Frank M. Bennet, *The Steam Navy of the United States*, Pittsburgh, Pa., 1896, p. 242.

CHAPTER 3

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2. David B. Steinman and Sara R. Watson, *Bridges and Their Builders* (reprint of 1941 ed.), New York, 1957, pp. 255–6.

   [Note: In connection with the perigean spring tide incident involving the Firth of Forth Bridge mentioned in the text of the present work, an explanatory detail is desirable. An obvious discrepancy occurs between the date of this happening ("New Year's Day of 1884") specified in the above-cited reference source and the date (May 26, 1884) given as that of the first actual constructional work, including caisson launching and implanting, in the immediately preceding paragraph of this same source.

   This inconsistency must also be considered against the confirmatory mention of an unusually high and low tide on the day of the accident—and the date (October 19, 1885) of subsequent surfacing of the caisson for the northwest corner of the Queensferry pier after its plunge to the bottom. Together, these evidences clearly indicate that the printed date for the accident should read "New Year's Day of 1885" instead of 1884.]
3. Ibid., p. 152.
4. F. D. Bickel, "Demolition of Ripple Rock," in *The Military Engineer*, vol. 51, No. 341 (May–June 1959), pp. 173–7.

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   [For April 7, 1958 in this article read April 5, 1958, and for Maude Island and Maude Inlet, read Maud Island and Maud Inlet, respectively.]

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CHAPTER 4

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5. *The Mathematical Principles of Natural Philosophy*, by Sir Isaac Newton, translated into English by Andrew Motte, etc., carefully revised and corrected by W. Davis, in three volumes, vol. III, London, 1803, pp. 241, 243.

   Also: Sir Isaac Newton's *Principia* (original Latin edition) reprinted for Sir William Thomson and Hugh Blackburn, Glasgow, 1861, pp. 465, 467.
6. *Encyclopaedia Britannica, or a Dictionary of Arts and Sciences Compiled Upon a New Plan*, etc., by a Society of Gentlemen in Scotland in three volumes, vol. I, Edinburgh, Scotland, 1771, p. 474.
7. John Hamilton Moore, *The New Practical Navigator*, etc., being an Epitome of Navigation, 12th edition, London, 1796, p. 133.
8. John Hamilton Moore, loc. cit.
9. D. L. Hutchinson, "The Saxby Gale," in *Transactions of the Canadian Institute*, vol. IX (1911), Toronto, 1913, p. 256.
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11. D. L. Hutchinson, op. cit., pp. 253–5.
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13. William Ferrell, "Report of Meteorological Effects on Tides," in the annual *Report of the Superintendent of the Coast Survey for 1871*, Appendix No. 6, Washington, D.C., 1874, p. 98.

    [Note: The sketch No. 38 referred to in the passage here quoted directly from the text of the article is a typographical error in the original publication and should read "Sketch No. 34."]
14. Horace Lamb, *Hydrodynamics*, 1st American printing of British 6th ed. (1932), New York, 1945, pp. 353–355.
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Part II

CHAPTER 3

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2. Hugh Godfray, *An Elementary Treatise on the Lunar Theory* (3d ed., revised) Macmillan and Co., New York, 1871, p. 64.

The historical development of the theories of lunar evection, variation, and other solar-induced perturbational terms since the time of Newton can be traced through the following sources:

(a) Sir Isaac Newton, *Mathematical Principles of Natural Philosophy* and His System of the World, translated (from Latin) into English by Andrew Motte in 1729 (from the 3d ed. of 1726); the translations revised, and supplied with an historical and explanatory appendix by Florian Cajori. University of California Press, Berkeley, Calif. (2d printing), 1946. Book I: The Motions of Bodies, Proposition LXVI, Theorem XXVI, pp. 173–182; also Book III: The System of the World, Proposition XXII, Theorem XVIII, pp. 433–434.

(b) Roger Long, *Astronomy*, in Five Books, Cambridge, England, 1764. Book 4, volume II, chapter 4: The Irregularities of the Moon's Motion Caused by the Attraction of the Sun, pp. 620–629, sections 1441–1458.

(c) Ferdinand R. Hassler, *A Popular Exposition of the System of the Universe*, G. & C. Carvill, New York, 1828. Part III, chapter III, pp. 88–94.

(d) John Gummere, *An Elementary Treatise on Astronomy*, in Two Parts, revised by E. Otis Kendall (4th ed.) E.C. &J. Biddle, Philadelphia, Pa., 1851. Chapter XXII, pp. 209–214, sections 404–407.

(e) Ernest W. Brown, *An Introductory Treatise on the Lunar Theory*, Cambridge University Press, London, England, 1896 (reprinted by Dover Publications, New York, 1960), pp. 124–130.

(f) Carnegie Institution of Washington (Publication No. 9), *The Collected Mathematical Works of George William Hill*, in four volumes, Carnegie Institution of Washington, Washington, D.C. 1905–1907. Volume I, memoir No. 29—On the Part of the Motion of the Lunar Perigee Which Is a Function of the Mean Motions of the Sun and Moon, pp. 243–270; volume I, memoir No. 32—Researches in the Lunar Theory, chapter II: Determination of the Inequalities Which Depend Only on the Ratio of the Mean Motions of the Sun and Moon, pp. 305–335; volume IV, memoir No. 51—The Secular Variation of the Motion of the Moon's Perigee, p. 105; volume IV, memoir No. 55—Literal Expression for the Motion of the Moon's Perigee, pp. 41–50.

(g) Forest Ray Moulton, *An Introduction to Celestial Mechanics* (2d rev. ed.), The Macmillan Co., New York, 1914. Chapter IX, section I: Effects of the Components of the Disturbing Force, pp. 325–332, and section II, The Lunar Theory, pp. 347–360.

(h) Dirk Brouwer and Gerald M. Clemence, *Methods of Celestial Mechanics*, Academic Press, New York, 1961. Chapter XII, Lunar Theory, pp. 324–328, and pp. 360–366.

CHAPTER 4

1. Rollin A. Harris, *Manual of Tides*, compiled from various technical appendixes to the annual *Reports of the Superintendent of the U.S. Coast and Geodetic Survey*, 1894–1907. U.S. Government Printing Office, Washington, D.C., 1895–1908. The pertinent reference appears in Appendix No. 9 of the annual report for 1897, Washington, D.C., 1898, part II, chapter IV, p. 525, equation 288.
2. Forest Ray Moulton, *An Introduction to Celestial Mechanics* (2d rev. ed.) The Macmillan Co., New York, 1914, p. 327.
3. U.S. Naval Observatory, *Improved Lunar Ephemeris*, 1952–1959, U.S. Government Printing Office, Washington, D.C., 1954, p. 317. The approximate equation given here contains only five of a series of 181 terms, the rest having very small coefficients.
4. This 1931 March 4 instance of an extremely small separation-interval between perigee and syzygy ($P-S=+6$ min.) ranks among the closest such alignments in the 400-year period 1600–1999.

Its positive effects upon tidal flooding potential are amply demonstrated in the multiple descriptions of coastal inundation which accompanied the strong perigean spring tides produced (see Key No. D–57) as noted in tables 1 and 5 and in chapter 7 of the text. The extended astronomical influence of this very close agreement between the positions of perigee and syzygy is further emphasized by a chain of five interrelated tidal flooding events in the space of 23 consecutive months. These events are separated by periods of 2, 1, 7.5, and 1 anomalistic months, respectively (see table 1). Each interval between floodings is indicative of the mathematically commensurable relationships which govern successive perigee-syzygy alignments and their associated perigean spring tides.

5. Edgar W. Woolard and Gerald M. Clemence, *Spherical Astronomy*, Academic Press, New York, 1966, p. 161.
6. An exact coincidence between the ascending node of the lunar orbit and the vernal equinox would require that the Moon be crossing the ecliptic (i.e., the apparent celestial latitude of the Moon, $\beta_{☾}=0°$, and increasing from $-$ to $+$) at the same time that the Sun is crossing the celestial equator from south to north (i.e., the apparent declination of the Sun, $\delta_{\odot}=0°$).

Although such an exact agreement is very rare, the attainment of the above conditions within a few days of each other is sufficient to produce the extreme lunar declinations noted in the text. See *The American Ephemeris and Nautical Almanac* for the year 1950, U.S. Government Printing Office, Washington, D.C., 1948, p. 4, pp. 60, 104, and pp. 134, 142.

CHAPTER 5

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4. Clyde Stacey, "Earth Motions," *The Encyclopedia of Atmospheric Sciences and Astrogeology*, vol. II, 1967, p. 337, col. 2.
5. U.S. Naval Observatory, *Improved Lunar Ephemeris*, 1952–59, U.S. Government Printing Office, Washington, D.C., 1954, pp. 286, 292; *Explanatory Supplement to The Astronomical Ephemeris and The American Ephemeris and Nautical Almanac*, Her Majesty's Stationery Office, London, England, 1969, pp. 44, 107; *Supplement to the A.E. 1968*, U.S. Naval Observatory, Washington, D.C., 1966 (reprinted with footnote revisions, 1973), pp. 16s–18s.
6. H. F. Fliegel and T. C. Van Flandern, "A Machine Algorithm for Processing Calendar Dates," *Communications of the Association for Computing Machinery*, vol. XI, No. 10, Oct. 1968, p. 657.

CHAPTER 6

1. Cf., Hugh Godfray, *An Elementary Treatise on the Lunar Theory*, New York, Macmillan and Co., 1871, pp. 73–74.

CHAPTER 7

1. George F. McEwen, "Destructive High Waves Along the Southern California Coast," *Shore and Beach*, vol. III, No. 2, April 1935, pp. 61–64 (especially p. 63).
   See also: Morrough P. O'Brien, "The Coast of California as a Beach Erosion Laboratory," *Shore and Beach*, vol. IV, No. 3, July 1936, pp. 74–79 (especially p. 74).
2. Dorothy Franklin, *West Coast Disaster*, Columbus Day, 1962, Gann Publishing Co., Portland, Oreg. (no publication or copyright date).

CHAPTER 8

1. Glenn W. Brier, "Diurnal and Semidiurnal Atmospheric Tides in Relation to Precipitation Variations," *Monthly Weather Review*, vol. 93, No. 2, February 1965, pp. 93–100.
2. John R. Gribben and Stephen H. Plagemann, *The Jupiter Effect*, Walker and Co., New York, 1974; reprinted, 1975, revised, 1976, Vintage Books, New York.
   For technical reviews of the proposed theory, see: *American Scientist*, vol. 62, pp. 721–722, 1974; *Annals of Science*, vol. 32, pp. 601–603, 1975; *Icarus*, vol. 26, pp. 257–267, 270, 1975; *Physics Today*, April 1975, pp. 74–75; and *Science*, vol. 186, pp. 728–729, 1974.

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A selected list of reference sources, arranged by category, as follows:

(1) CLASSIC WORKS AND TREATISES ON THE TIDES (See also category 8.)
(2) TEXTBOOKS AND SURVEY WORKS ON PHYSICAL AND DYNAMICAL OCEANOGRAPHY
(3) REFERENCE AND GENERAL SUMMARY ARTICLES ON THE TIDES
(4) DESCRIPTIVE WORKS AND POPULAR PRESENTATIONS ON THE TIDES
(5) THE EARTH-MOON SYSTEM; CLASSIC THREE-BODY PROBLEM; LUNAR THEORY AND PERTURBATIONS; EARTH TIDAL INFLUENCES ON THE MOON'S ORBIT (See also category 25.)
(6) GRAVITATIONAL FIELDS OF THE EARTH, MOON, AND SUN; TIDE-GENERATING FORCES AND THE GRAVITATIONAL POTENTIAL (See also category 7.)
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(42) BIBLIOGRAPHIES, SOURCE BOOKS, GLOSSARIES, AND STATE-OF-THE-ART LITERATURE RELATIVE TO TIDES AND TIDAL CURRENTS

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Portion of barrier beach south of Mecox Bay, near Southampton, Long Island, N.Y., breached by tidal flooding of March 6-7, 1962.